Study on Correlation Between Particulate Matter Emissions and Exhaust Smoke Levels in CI Engines

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Abstract. Particulate Matter is one of the harmful exhaust emissions that effect both environment and human health. Various universities and research centers often estimate the level of Particulate Matter through the smoke levels. For more than 3 decades, researchers are trying to validate the existing correlation between Particulate Matter emissions and exhaust smoke levels. While the measuring principles of both pollutants follow similar principles, the cost and operation associated with them are widely different. Instruments that measure Particulate emissions that are released from the engine exhaust are very valuable because of their high cost, unavailability of skilled technicians and maintenance of equipment. While some proposed that dark substance from the exhaust and on smoke filter is because of the presence of the primary component of the particulate matter, soot, others proved it with results of their experiments. In this article, we will study the research results that prove the existing correlation between the both. It is observed that the particulate matter and smoke opacity follow a linear relationship.

Keywords: Particulate matter · Smoke · IC engines · Exhaust emissions

1 Introduction

Exhaust emissions from automobiles are one of the primary sources of pollution disrupting the environment and damaging human health. Studies reveal that almost 60–70% of damage that is being done to the atmosphere is caused due to the release of harmful emissions from automobiles. These pollutants get deposited on the leaves and damage the crops. And the damage is not confined to atmosphere, certain pollutants such as Particulate Matter (PM) are the reason for respiratory and cancerous diseases [1–3].

Of all the diesel emissions, PM is one of the most problematic emission that directly effects the health of human. Numerous research and studies are underway to determine the ways to substantially decrease the release of particles of size less than 2.5 microns. Although automobiles and industries prevent the particulate matter from entering into the atmosphere by installing filters, some particles which are less than 2.5 microns, which are difficult to be filtered through conventional filers, gets released. These particles enter into human body damaging the respiratory system and lungs. When compared to

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other emissions, the intensity of harm caused by PM to the environment and direct and immediate impact on human health is relatively high [4–6].

Briefly, the primary reason for the formation of Particulate matter in a CI (Compression Ignition) engine can be categorized into inhomogeneity of air-fuel mixture and the deficiency of oxygen for the last injected fuel. Particulate matter consists of unburnt hydrocarbons, soot (elementary carbon), sulfur and unburnt lubricating oil particles. It is emitted from engine exhaust as black smoke and hence the intensity of smoke is considered to be directly proportional to the PM levels [1, 7, 8].

Black smoke which is released by the diesel consists of carbon particles which are released by thermal cracking of large hydrocarbon fuel molecules. Smoke production can be decreased by decreasing the time taken for diffusion combustion. This can be done by having rapid mixing of air and fuel mixtures or by adjusting the injection timing. By advancing the injection, we are allowing more time for the expansion stroke for oxidation thereby reducing smoke. Smoke production is also directly influenced by load in linear manner.

Smoke levels or opacity in the exhaust emissions are believed to maintain a stable relationship with the levels of particulate matter in the fuel. Often times, smoke levels are measured for the determination of particulate emissions, in the belief that with reduction in smoke levels there is less particulate matter in the exhaust gas. There has been a pre-existing correlation between these two emission parameters [9, 10]. Many studies have been conducted over the last 3 decades validating the correlation between PM emissions and smoke levels [9–13]. The measurement of PM often involves highly efficient staff and precise equipment, which often consumes high amount of time and huge sums of money. Although those equipment's are used in places that requires topmost precession, often times in universities and research institutes, it is replaced by simpler and uncomplicated smoke measuring instruments which provide an estimation of exhaust PM [8, 11].

We plan to begin the article with the study of similarities between measuring principles associated with Smoke levels and Particulate emissions followed by the analysis of the test results that proves a linear relation between the two. This gives a better understanding of reasons for the correlation.

The primary aim of this article is to study the correlation between Smoke level and Particulate Matter emissions. This research article has 2 main objectives, 1. To understand all of the principles that are associated in the measurement of Smoke and PM. 2. To analyze the research results of experiments that were previously conducted and study their result to find any significant correlation.

2 Literature Review

The measurement of Particulate Matter and Smoke levels are researched in this literature review for a better understanding of the principles associated with measuring each of the pollutants. With the apprehension of similarities in the measuring principles, it would be easy to understand the research results, which are discussed in detail in the following chapter.

2.1 Measurement of Particulates

Instruments that are used to measure particulate matter work either by measuring the particle size distribution or by measuring the concentration of the PM.

Gravimetric method is used to get more accurate readings. In this method air is drawn into a filter where the particles are collected. The weight of this filter is taken before and after the air is drawn and the sample is collected. It is then compared and analyzed. By doing so, the particles can be collected in their raw form and enables us to analyze the composition of the particles chemically.

This test is done with high accuracy and precision, it is generally used in governing bodies like European Union where high standards are required. The primary drawback of this test method is that it only measures the PM emissions at that point of time, no real time data is produced. Other downsides of this method are the cost and professionals that are required for conducting the tests.

The volumetric way of measuring Particulates is by weighing a filter paper before and after passing a certain volume of exhaust gas. It is a slow process and cannot be used in rapid testing purpose.

A rapid way of testing is by using an e-Tapered Element Oscillating Micro-balance (TEOM) detector. Here, a very small filter paper is fitted to the narrow end of a tapered tube in 50 °C constant-temperature oven. The tube is left free at the filter corner and held from the wider side. The flow of particulates is calculated by monitoring the change in mass of the assembly. As a cantilever, tube is excited to vibrate in its natural frequency and the mass is measured. According to the below relation, the filter mass rises as the natural frequency declines:

$$f = \sqrt{\frac{k}{m}}, \tag{1}$$

where f – frequency (rad/sec); k – spring rate (N/m); m – mass (kg).

Using this process, Particulate mass flow is updated at <2 Hz.

Optical instruments can also be used for measuring the PM concentration. By examining and understanding how it reacts with different lights. Optical particle counter (OPC) is one such method where a laser diode (source of light) is passed to illuminate the particles. The scattered light due to the presence of particles is then measured using a photodetector. Flame Ionization Detector method can also be used to determine the real time results.

To show its concentration in the air, PM is expressed in micrograms per cubic meter ($\mu g/m^3$). This concentration level is then compared to the standard Air Quality Index (AQI) which is divided into 6 categories depending on the level of health concern associated with the pollution [14–16].

2.2 Smoke Measurement

Smoke measurement is a clear indication of efficiency of the combustion process. It can be measured using 2 principles, reflectivity or opacity.

During the measurement of smoke using the principle of reflectivity, a filter paper is fitted and a known volume of exhaust is sent through the paper. The reflectivity of that filter paper is analyzed after this process and compared with the scale. Bosch meter is one such instrument that measures the smoke in terms of reflectivity. A perfectly clean paper is given with a 0 value and 10 in Bosh scale indicates that it does not reflect any light at all.

A continuous monitoring is not possible with this meter as the filter paper is needed to be replaced and it takes certain time for the known amount of exhaust to pass through the filter paper [17].

Smoke is predominantly measured using the principle of opacity. Opacity measurement is the assessment of optical properties exhibited by the diesel exhaust. They quantify the black smoke emission with the help of a light beam. It, to some degree, works in the same phenomenon explained in case of quantification of Particulate matter measurement. Although the function is similar, opacity meters are much simpler and cheaper compared to the instruments used in the particulate measurement [18].

3 Study of Research Results and Discussion

In a test, carried by Sung et al., to validate the existence correlation between the smoke level and particulate mass in a directly fuel-injected single cylinder engine equipped with a Protech, V-smoke meter and PM collector, they confirmed the preexisting relationship between PM emissions and smoke levels to be true and proportional (see Fig. 1) [9].

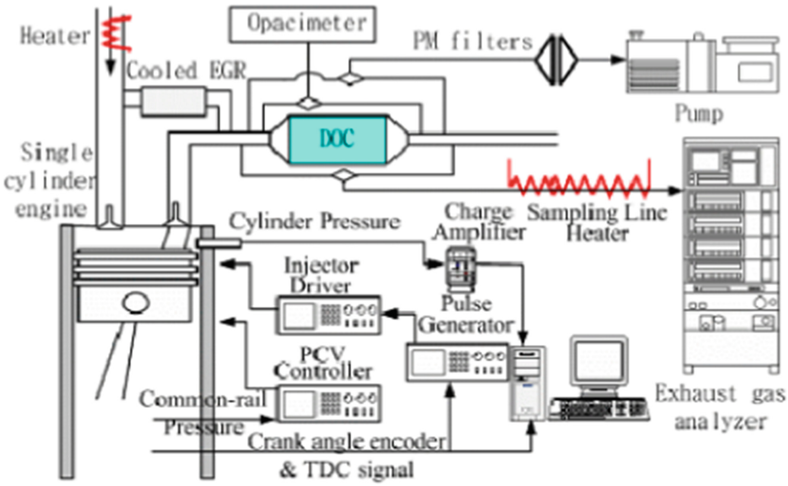

Fig. 1. Sung et al.'s experimental schematic diagram.

As shown (see Fig. 2), particulate matter is observed to change with load but maintained a steady and proportional relation with smoke level. This linear relation helps research centers and universities in replacing the cost burden and complex PM measuring equipment with that of convenient Smoke Opacity meters.

In another research, with an attempt to provide a low-cost, indirect PM measuring method at an assumed accuracy, Merkisz and Pielecha presented an article comparing

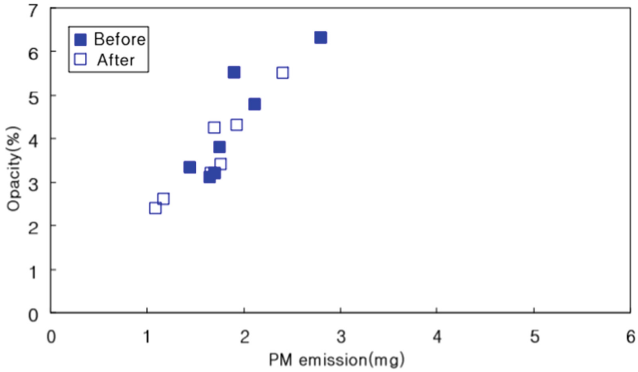

Fig. 2. Sung et al.'s correlation between smoke and PM emissions in diesel combustion.

Horiba 1220 PM analyzer (PM emission) results with those of indirectly tested PM results of AVL 438 Opacimeter which measures the exhaust gas smoke value. The tests are carried out on a 4-cylinder common rail diesel engine (see Fig. 3) [14].

After analyzing their results (see Fig. 4), it is concluded that it is possible to estimate PM levels through the smokiness in the exhaust gas. They also found a significant correlation where the R^2 coefficient (coefficient of determination) is above 0.5 between the hourly particle emission and exhaust smoke. It suggests the possibility of substitution of Horiba analyzer (0.7 R^2) with opacity meter (0.9 R^2).

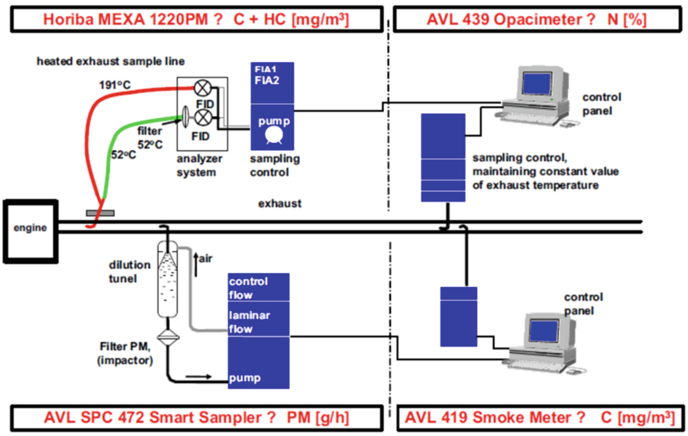

Fig. 3. Merkisz's test apparatus.

In an attempt to address the correlation between opacity and particulate emissions, Hassami and Child performed a statistical analysis to develop empirical equations to calculate Particulate Emissions in terms of Opacity (one of the factors). One of their specific areas covered in their research is to provide a reasonable approximation in the

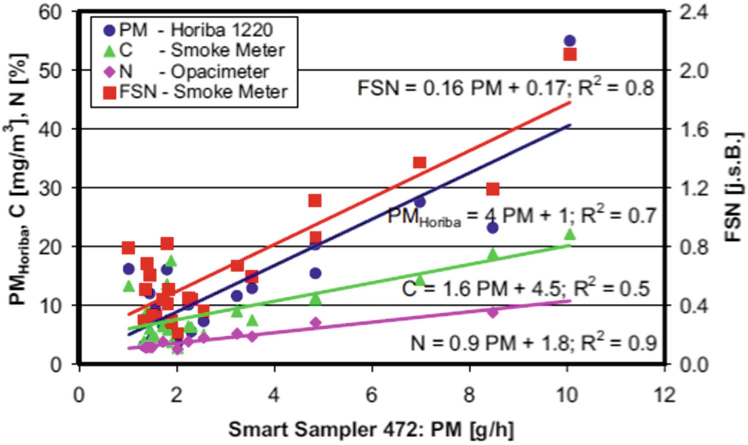

Fig. 4. Merkisz's test results of Correlation of particle emissions and exhaust smoke.

estimation of their interdependency. Data was collected from 72 vehicles (see Table 1) across different types [11].

Table 1. Tested vehicle categories.

Vehicle description	Number of vehicles tested
Passenger/off road passenger ≤ 9 seats	12
Heavy bus	6
Light Goods vehicle	18
Medium goods vehicle	14
Goods vehicle	13
Heavy goods vehicle	9

After analyzing the results of their research, they found that a linear relationship is found between particulate matter and average opacity with an R^2 coefficient value of 0.87 (see Fig. 5). They concluded that they found the best model for predicting particulate matter. While their research included many other factors like vehicle mass, fuel consumption, O_2, CO, CO_2 and NO_X, the graph showing the relationship between average opacity and Particulate Matter is what lies in our interest.

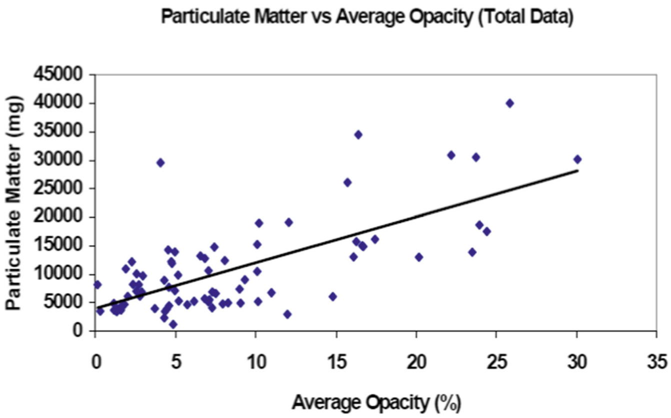

Fig. 5. Particulate – opacity relationship.

4 Conclusions

1. Of all the emissions from an Internal Combustion engine, the harmful effects of PM to agriculture, environment and direct and immediate impact on human health is relatively high and widely studied.
2. Particulate matter, which is a mixture of unburnt hydrocarbons, soot (elementary carbon), sulfur and unburnt lubricating oil particles is emitted from engine exhaust as black smoke and hence the intensity of smoke is considered to be directly proportional to the PM levels.
3. For more than 3 decades, some researchers measure smoke levels for the determination of particulate emissions, in the belief of a preexisting correlation that with reduction in smoke levels there is less particulate matter in the exhaust gas.
4. Instruments needed for PM measurement often involves highly efficient staff and precise equipment. They are costlier and takes a lot of time to be precise. These instruments are often used in places that requires topmost precession.
5. Gravimetric method is often used for PM measurement. In this method air is drawn into a filter where the particles are collected. The weight of this filter is taken before and after the air is drawn and the sample is collected. It is then compared and analyzed. It also analyzes the chemical composition of the particles.
6. Although this method is precise it provides no real time data. Other downsides of this method are the cost and professionals that are required for conducting the tests.
7. Smoke Opacity is the assessment of optical properties exhibited by the diesel exhaust. They quantify the black smoke emission with the help of a light beam. Although the function is similar, opacity meters are much simpler and cheaper.
8. Almost all the research results that are studied shows a linear relationship between Particulate matter emissions and exhaust smoke levels. While there is a long existing correlation between Particulate matter and Smoke levels, this article presents all the results and analysis that proves it to be true.

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