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Challenges in PM Measurement at 1 mg/mile and Tunnel Background Correction

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Abstract

The LEV IV FTP PM limit in the recently approved CARB ACC II regulations for passenger cars and light duty trucks will be 1 mg/mile starting in 2025. Gravimetric PM measurement at these levels is very challenging as the net mass of PM on the filter in full flow tunnel testing ranges between 8 to 32 micrograms depending on amount of dilution. This is approaching tunnel background levels which, in combination with filter handling, static charge removal and microbalance instability, compounds the uncertainty. One major source of the uncertainty at these low levels is the tunnel contamination resulting in high variability from test to test and cell to cell. This tunnel background is mostly HC artifact which cannot be easily controlled and can be significantly higher than the 5-µg CFR allowable correction limit in some test cells. Items that might affect the PM background include the type of testing being run on the tunnel prior to measuring the background such as OBD, cold and diesel testing. Quantifying the contribution of these artifacts and how they play into the overall uncertainty cannot be easily determined at this time. Regular conditioning and cleaning of the tunnel to keep the tunnel background below the 5-µg limit has shown to be crucial at these low levels. The process to drive contamination out and reduce the tunnel background below 5 µg will be described. A model is created to determine the range of net PM mass on the filter at 1 mg/mile with different CVS flowrates. The current process of tunnel background measurement and correction will be discussed. Countermeasures to reduce the uncertainty in PM measurement at 1 mg/mile PM level will be explored.

Introduction

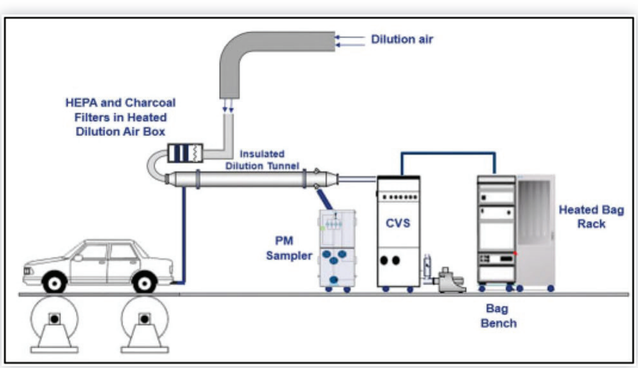
PM emission standards have been steadily decreasing over the last 40 years. The light duty PM limit on passenger cars and light duty trucks was at 0.2 g/mile in 1987, but the introduction of diesel particulate filters (DPF) in the mid 1980's allowed regulators to significantly lower the PM limit, which has been steadily decreasing ever since. The PM standard dropped to 0.08 g/mile in 1994, then to 0.04 g/mile in 1998, and to 0.01 g/mile in 2006. More recently, increased trends in higher compression ratios, turbocharging and downsizing resulted in a steady increase in production of gasoline direct injection (GDI) technologies to improve fuel economy and reduce greenhouse gas. PM emissions from GDI vehicles are approximately an order of magnitude higher than those from port fuel injection (PFI) vehicles. Due to the increased trend in GDI production, the California Air Resources Board and the EPA adopted in 2017 a new LD PM limit of 0.003 g/mile on the Federal Test Procedure (FTP) cycle. Even though there has been over a 98% decrease in the limits over the past 30 years, The California Air Resources Board (CARB) approved a new PM limit of 1 mg/mile starting in 2025 as part of the ACCII LEV IV regulation [1]. The 1 mg/mile standard may require adding a gasoline particulate filter (GPF) on GDI vehicles which may have counter effect of fuel economy and greenhouse gas due to increased backpressure in the exhaust system. GPF and DPF technologies may sound similar but there are some variations in the filter formulation, functionality, and control strategy, because of the differences between gasoline and diesel fuels, engines operating conditions, emission rates of particulates and PM composition. A lot of research has been focusing over the last few years on GPF development especially for Euro 6 applications where, in addition to a PM mass standard, a particle number standard of 6 x10^{11} particles /Km is required to be met on all vehicles sold in Europe. Dadam [2] developed a unique system with architecture and OBD controls required to detect a disconnected or plugged hose when combining a differential pressure (dP) sensor and an electronically controlled exhaust butterfly tunning valve positioned in the exhaust system downstream of the GPF which is used to control noise levels.

The 1 mg/mile PM limit is challenging to meet on vehicles with or without GPF / DPF in terms of measurement resolution, reliability, and repeatability. The net weight of PM to be measured on the filter will range between 8 and 32 micrograms depending on the CVS flow rate and amount of dilution. Many authors have reported the presence of artifacts in the air and dilution tunnel background [3,4,5,6,7,8,9,10] that saturate the PM filter. The tunnel background or tunnel blank is defined as the filter net mass of PM or weight gain in micrograms when running a blank test sampling dilution air from the dilution tunnel over the filter which gives an indication of how clean or dirty the tunnel background is for correction purposes. In addition to the artifact from the dilution air and tunnel background, other sources of uncertainty cause measurement errors such as filter handling by the operators, static charge removal and environmental conditions in the weighing chamber and in the test cell when the filter is being transported for testing.

The gravimetric method on full flow dilution system has been used by the industry to measure PM for over 40 years. The procedure for PM measurement in full dilution sampling system is defined in the code of Federal regulations in Parts 1065 [11] and 1066 [12]. The LD PM sampling system typically includes a full dilution tunnel coupled to a constant volume sampler where a PM sample is drawn from the tunnel by a sampler which controls the flow over the filter and control the switch over from filter to filter at the right time between the different phases of the test. Figure 1 shows the test cell layout with a 48 inch dynamometer, full dilution tunnel, constant volume sampler (CVS), PM smart sampler and emission analyzer bag bench. The flow over the filter is quantified by controlling the filter face velocity (FFV).

In addition to full flow, partial flow dilution systems are also approved for testing by the CFR part 1065 and 1066 for both LD and HD applications. Partial flow sampling takes a small fraction or a partial sample from the vehicle exhaust rather the full exhaust flow and dilutes this sample with clean, filtered shop air proportionally to the exhaust flow. Partial flow PM systems are more desirable for HD applications compared to full flow but they are more complex because the sample ratio needs to be carefully controlled proportionally to the continuously varying exhaust flow under transient conditions. The major advantage of using partial flow systems is that they are much smaller and cheaper instruments which do not require bulky CVS systems espcially for HD larger engines. Khalek et al [13] investigated the correlation between partial flow and full flow PM systems for HD applications while Johnson et al [14] and Maricq et al [15] conducted their study on a LD application and they all concluded that Partial flow correlated well to full flow. Fanick et al [16] investigated the measurement of polycyclic aromatic hydrocarbons and hydrocarbon speciation in diesel exhaust and concluded that that a partial flow dilution sampling system compared favorably to a full flow system. While there were some differences for the lower molecular weight PAH, most of the volatile hydrocarbons and higher molecular weight PAH were similar between the two different methods of sampling these compounds. Although this study did not involve partial flow systems, I would predict that the contamination in partial flow sampling would be easier to deal with in comparison to full flow because of the much smaller surface area in the sampling system for artifacts to adhere to. It will also be much easier to tear down a partial flow sampling system for cleaning and reducing contamination if hot testing could not do it alone.

FIGURE 1 PM Sampling System and Test Cell Layout



CFR Part 1065 added many new requirements and recommendations to improve the PM measurement and reduce variability. Below are some of these requirements / recommendations:

- Reference filters must remain in weighing chamber to monitor the filter weights before every weighing session and must remain within ± 10 μg or ± 10 % of the net PM mass expected at the standard
- Pure PTFE filter material to lessen the artifact deposition on filter
- Buoyancy correction for PM sample media density, density of air, and density of the calibration weight used to calibrate the balance
- Polonium strips to remove static charge on the PTFE filters
- Ambient and dewpoint temperature tolerances of 22 ± 1 °C and 9.5 ± 1 °C respectively
- Recommendation of Class Six clean room specifications for the weighing chamber maintaining the environment free of ambient contaminants, such as dust, aerosols, or semi-volatile material that could contaminate PM samples
- Maximum air-supply and air-return velocities of 0.05 m/s in the weighing environment
- The microbalance to be placed on a vibration-isolation platform to isolate it from external noise and vibration
- Electrically ground the microbalance
- Operators to use 300 series stainless-steel tweezers that are electrically grounded
- Substitution weighing to reduce variability in PM filter weighing

Most the above listed recommendations and requirements are also described in more detail in SAE J2943 [17] which is a Recommended Practice for Filter Weighing of handling. This is expected to get worse at 1 mg/mile if countermeasures are not addressed to mitigate their effects. Errors in filter handling can be minimized by limiting the weigh room to one operator per shift and one backup, regular cleaning of filter holders and weighing room, operators wearing appropriate gloves and lab coats and using sticky mats when entering the weighing room.

- Tunnel contamination is one of the major sources of variability. Tunnel conditioning and cleaning must be performed regularly to keep the background as low as possible. Background correction can approach the net PM filter weight being measured especially on larger vehicles which have to run at higher CVS flow rates. One way to avoid higher tunnel backgrounds from affecting tests with very low PM is to condition / clean the tunnels regularly by running hot testing to achieve a tunnel gas temperature of about 80 °C at the PM sampling location. It is also recommended to segregate test cells to avoid cross contamination from dirty vehicles and OBD testing that may affect PM results on clean vehicles
- The corrected net mass of PM on the filter at the 1 mg/mile will be less than 30 µg at a CVS flowrate of 250 CFM (7 m^3/min) with a 50% engineering target. This net PM mass will decrease as the CVS flow rate goes up for larger vehicles and can be as low as 3 µg after tunnel background correction at a 1000 CVS flow rate. The correction at this level can be as high as 168% of the actual net corrected PM mass being measured. This 3 µg is within the range of variability of many of the subcomponents (tunnel background, microbalance instability in filter weighing, filter handling by the operators, static charge removal which will all affect PM mass on the filter at this level.
- Higher CVS flow rates needed on larger vehicles will cause the sample ratio to increase to values larger than 450 at higher CVS flow rates of about 1000 CFM (30 m^3/min). Any error in measurement due to a non-corrected tunnel contamination, poor handling of the filter, static charge removal, or microbalance instability gets magnified by the same sample ratio (450 times or higher). This will significantly amplify the errors and uncertainty in measurement at this low level. It is very important to optimize the CVS dilution and avoid over dilution while complying with CFR Part 1066 DF requirements.
- In summary, PM measurement at 1 mg/mile is approaching noise and tunnel background levels. The uncertainty in measurement stems from many possible sources. Countermeasures must be carefully followed for each possible source to lessen the impact of these uncertainties and minimize variability.

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Definitions/Abbreviations

ACC II - Advanced Clean Car Act II
CARB - California Air Resources Board
CFM - Cubic Feet per Minute
CFR - Code of Federal Regulations
CVS - Constant Volume Sample
DF - Dilution Factor
DPF - Diesel Particulate Filters
DR - Dilution Ratio
EC - Elemental Carbon
EPA - Environmental Protection Agency
FFV - Filter Face Velocity
FTP - Federal Test Procedure
GDI - Gasoline Direct Injection
HD - Heavy Duty
LD - Light Duty
LEV - Low Emission Vehicle
OC - Organic Carbon
OBD - On Board Diagnostics
PM - Particulate Matter

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