

The Role of EGR in PM Emissions from Gasoline Engines

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ABSTRACT

A dilute spark-ignited engine concept has been developed as a potential low cost competitor to diesel engines by Southwest Research Institute (SwRI), with a goal of diesel-like efficiency and torque for light- and medium-duty applications and low-cost aftertreatment. The targeted aftertreatment method is a traditional three-way catalyst, which offers both an efficiency and cost advantage over typical diesel aftertreatment systems. High levels of exhaust gas recirculation (EGR) have been realized using advanced ignition systems and improved combustion, with significant improvements in emissions, efficiency, and torque resulting from using high levels of EGR. The primary motivation for this work was to understand the impact high levels of EGR would have on particulate matter (PM) formation in a port fuel injected (PFI) engine. While there are no proposed regulations for PFI engine PM levels, the potential exists for future regulations, both on a size and mass basis. To determine the effect of EGR on PM emissions, a 2.4L, 4-cylinder PFI engine was run at a variety of part and full load conditions. PM and gaseous emissions were measured at each condition, with the PM measurements consisting of both mass and particle size/number measurements.

This work indicated that an engine operating in the fuel enrichment region produces a significant amount of PM. As modern gasoline engines move to higher specific power levels, the size of the enrichment region, in terms of percent of the total engine performance map, increases significantly. By using EGR to reduce combustion temperatures and eliminate the need for enrichment, the PM mass and number emissions were reduced substantially. Comparisons in the enrichment regime indicated the primary benefit of EGR was from eliminating enrichment, but a significant benefit was found from using EGR even at rich conditions. EGR also reduced PM emissions at part load conditions, particularly

those above 50% load. An analysis of the PM measurements combined with the gaseous emissions indicated that the addition of EGR reduces combustion temperatures, suppressing the PM formation mechanism more than the oxidation / destruction mechanisms, resulting in an overall PM emission reduction.

INTRODUCTION

PM emissions have long been a concern of those involved with regulating the diesel industry, as the PM emissions from diesel engines have been shown to be significant and are believed to be a health hazard. With the advent of the GDI engine, PM emissions have become a source of concern for the gasoline industry also [1]. Several studies have been performed to understand the mechanism by which GDI systems yield increased PM and/ or HC emissions [2,3,4,5] with significant effort going into designing GDI engines to avoid PM emissions (see e.g. [6]). This is particularly relevant since the Euro V light-duty emissions standard have a 0.005 g/km limit on PM emissions from GDI-equipped vehicles and the US Tier II Bin V standard is 0.01 g/mile for all diesel vehicles [7], with expectations that future regulations will constrain gasoline-fuelled engines also.

In general, GDI engines have elevated PM emissions due to the presence in the combustion chamber of liquid fuel, which has been extensively documented by multiple researchers [2, 8,9,10,11,12,13]. The presence of these liquid fuel deposits leads to higher HC and PM emissions, as they create locally rich areas within the combustion chamber, even when the global equivalence ratio is lean. PFI engines have lower levels of PM, primarily due to improved fuel vaporization and mixing. Even in PFI engines, however, there is the potential for small, but measureable PM emissions [14-15]. While the typical response to reduce PM emissions has been to employ a particulate filter in the engine aftertreatment, engineers working on diesel engines have shown that the use

of high levels of EGR can cool combustion temperatures enough to suppress PM formation [16-17]. Since it is unlikely that liquid fuel can be completely eliminated from gasoline fuelled engines (even PFI engines have some amount of liquid fuel entering the combustion chamber), the purpose of this study is to investigate the effect that cooling combustion and post-combustion temperatures with EGR has on the PM formation rate.

Previous work on EGR in gasoline engines has demonstrated that engines running moderate to high levels of EGR experience reduced combustion temperatures [18,19,20]. As reported, these reduced combustion temperatures result in lower emissions of CO and NO_x as well as lower engine-out exhaust gas temperatures. The reduction in pre-catalyst (in an NA engine) or pre-turbine (in a boosted engine) temperature means that enrichment can be avoided using EGR. In addition to lowering in-cylinder and exhaust temperatures, the use of EGR has been shown to reduce knock at high loads and pumping losses at low loads [18,19,20], resulting in improved fuel efficiency. The decrease in combustion and post-flame temperatures can also lead to increased HC emissions, with lower post-flame temperatures resulting in reduced oxidation of the crevice HCs. A key factor in this study will be to establish if the reduction in PM formation from cooler combustion temperatures is offset by a corresponding decrease in PM oxidation and what the resulting net change will be in PM emissions.

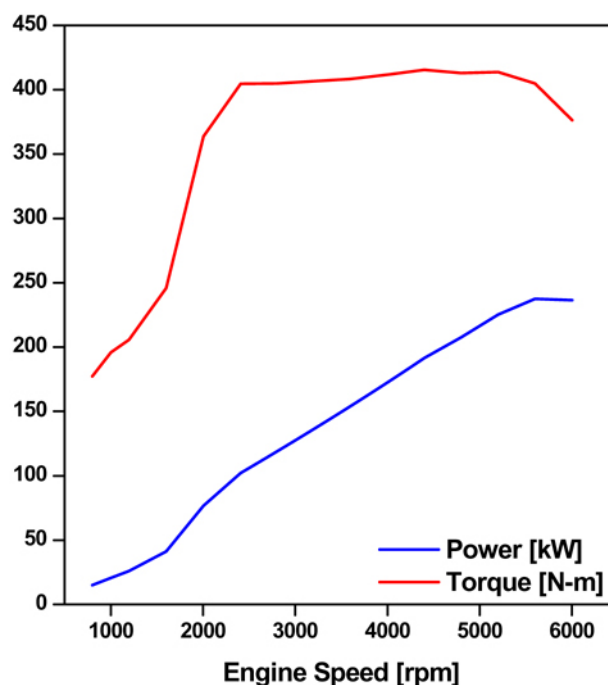


Figure 1. 2.4L engine (top: image; bottom: stock torque and power curves)

EXPERIMENTAL SETUP

The engine used in this study was a 2.4L PFI engine (Figure 1) and has been used in previous studies at Southwest Research Institute [18, 21]. The 2.4L engine has a peak torque of 400 N-m @ 2400 rpm and a peak power of 240 kW @ 5600 rpm (Figure 1). The engine was port fuel injected and also employs variable camshaft phasing on both the intake and exhaust cams. In stock form, the engine operates at 8.6:1 compression ratio, which was increased for these tests to 11.4:1 for high EGR operation.

One of the most important parameters in improving the dilution tolerance of the engine is the ignition system. For these tests, the spark plugs in both of the engines were upgraded from the stock plugs, which had relatively large,

nickel-coated copper center electrodes, small gaps and traditional ground straps. The new plugs had a very fine (< 0.6 mm) iridium center electrode and a similar, precious metal electrode on the ground strap. To promote dilution tolerance, the plugs were deployed with a very large gap of 1.65 mm. In addition to the upgraded spark plugs, a proprietary ignition system was used to improve the energy delivery and EGR tolerance of the engine.

Finally, a prototype EGR system was installed on each engine. Figure 2 shows the EGR system layout for the EGR system employed on engine. The system consisted of an EGR cooler and valve, installed in a Low-Pressure Loop (LPL) configuration. A cooler was installed in the EGR loop, upstream of the EGR valve, to reduce the EGR temperature to ~ 100-120° C. The LPL EGR design was chosen to limit backpressure on the engine at high loads, reducing the amount of hot internal residual and knock at these conditions. At low loads, the engine has limited tolerance for cooled EGR and dilution was provided by increasing valve overlap using the dual cam phaser system.

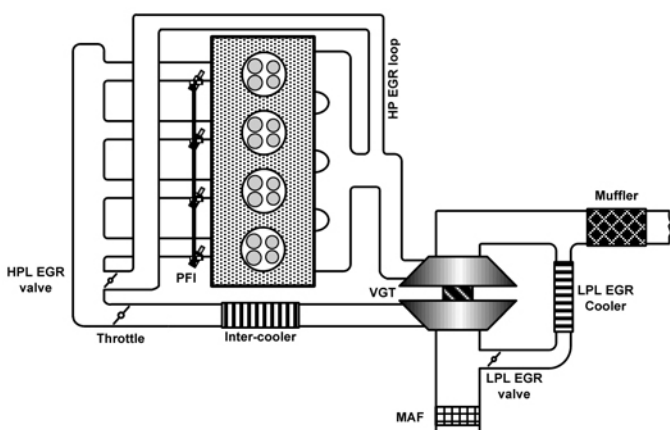


Figure 2. EGR system layout for the 2.4L engine

All emissions were measured on an engine-out basis. A Horiba 5 gas exhaust analyzer was used to measure carbon dioxide (CO₂), carbon monoxide (CO), oxygen (O₂), total hydrocarbons (THC), nitric oxide and nitrogen dioxide (NO_x) in undiluted engine exhaust. Particulate matter was measured in two ways. Mass was measured with a ‘partial dilution / partial sample’ based on EPA part 86, and used Whatman PP47 filters. Particle count and size was measured with an Engine Exhaust Particle Sizer (EEPS™) spectrometer. The EEPS is a state of the art particle sizing instrument that measures the number weighted size distribution of particles every 200 ms. EEPS cover a size range from about 5.6 to 560 nm with a resolution of 16 channels per decade. An aerosol stream enters the instrument through a 2 micrometer cut cyclone at a nominal flow rate of 10 lpm and a pressure of 1 bar. The aerosol is then subjected to two unipolar diffusion chargers. First, the aerosol is exposed to a negative charger to

reduce the number of highly positively charged particles and to prevent overcharging in the second charger. Second, the aerosol is exposed to a positive charger that puts a predictable net positive charge on the particles. The positively charged aerosols enter the mobility section that consists of 22 electrometers and a central rod that is divided to three insulated sections each maintained a different voltage level. The upper section is set at 85 volts, the middle section is at 470 volts, and the lower section is set at 1200 volts. Small particles are deposited first on the upper electrometer and large particles are deposited on the bottom [11]. Figure 1 shows a schematic of the detection unit.

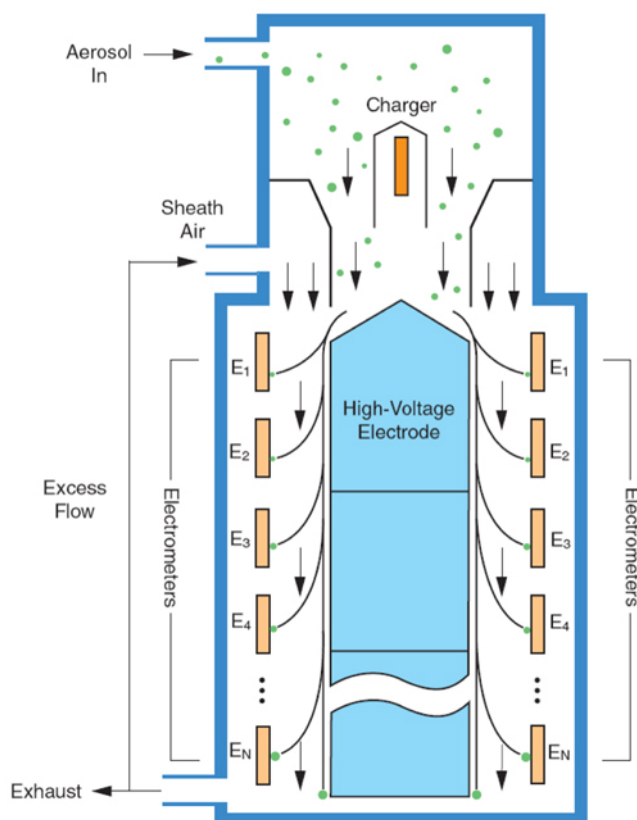


Figure 3. EEPS Detection Unit

The EEPS analyzer was used in an apparatus that enables detection of both the total particle count and size distribution and the solid particle count and distribution. Total particle count was determined by sampling the exhaust directly. The solid portions are the particles that would not be oxidized by a catalyst. The solid portion represents the particles that would actually be emitted out the exhaust or measured on a filter. To segregate the solid particles, the exhaust was sent through a catalyst before entering the EEPS analyzer.

All four exhaust measurements (gas-phase emissions, PM mass, solid and total PM size and count) were conducted concurrently after the engine was given a 5 minute stabilization period. Testing was conducted at three part load

engine operating conditions and at full load (Table 1). MBT spark timing and stoichiometric AFR were maintained unless specifically noted. MBT spark timing was assumed when the location of 50% mass fraction burned (50% MFB) was located 6-8 degrees after top dead center (aTDC). Intake and exhaust cam phasing were optimized at each condition for best brake specific fuel consumption (BSFC). Intake manifold temperature was allowed to vary depending on operating condition, but not allowed to exceed 50° C. Fuel injection timing was on a closed valve and held constant for all test points at TDC of the compression stroke. Full load was determined using 25% EGR with BMEP constrained by the boosting hardware or combustion stability. When operating without EGR, enrichment beyond stoichiometric was necessary in some instances due to excessive exhaust temperatures at the higher load conditions. For the exhaust hardware on the engine, the maximum allowable exhaust temperature was 820° C.

At low loads, the engine does not tolerate cooled EGR well, preferring either hot EGR (difficult with a LPL setup) or internal EGR. Therefore, at the 2000rpm and 2 bar BMEP condition no external EGR was used. Internal EGR was implied through valve timing and overlap, but no measurement of the actual trapped residuals was conducted. Instead, a 1-D simulation was used to estimate internal residual.

Table 1. Testing Conditions

Speed [rpm]	BMEP [bar]
Part Load	
2000	2
2500	6.7
3500	9.6
Full load	
1500	10
2000	12.5
3500	15

RESULTS AND DISCUSSION

The results section will examine the response of the engine to EGR at part load conditions prior to discussing high load results. In addition to the brake specific particulate measurements, some information on particle size distribution will be presented. Finally, for completeness, data regarding the other criteria pollutants will be presented so that the effect of the EGR can be evaluated on all regulated pollutant simultaneously.

PART LOAD CONDITIONS

The part load conditions, as detailed in Table 1, were selected to be representative of typical drive conditions. Typically, a

PFI engine operating correctly has PM emissions much lower than a comparable GDI or diesel engine. In the future, it is likely that PFI engines may encounter a requirement to reduce their emissions, particularly the emission of very small particles ($< 2.5 \mu\text{m}$).

The first condition examined was 2000 rpm / 2 bar bmep. The emissions results are shown in Figure 4. At this speed / load condition, dilute combustion was achieved increasing the level of valve overlap, increasing internal EGR (iEGR). Previous work has shown that the most desirable condition at low loads (bmep < 5 bar) is to have the charge temperature at intake valve closing as hot as possible. When using LPL EGR, as this engine employs, the most effective method of achieving this condition was to use iEGR. The result in Figure 4 for the internal residual level was not measured but instead estimated using GT Power cycle simulation software.

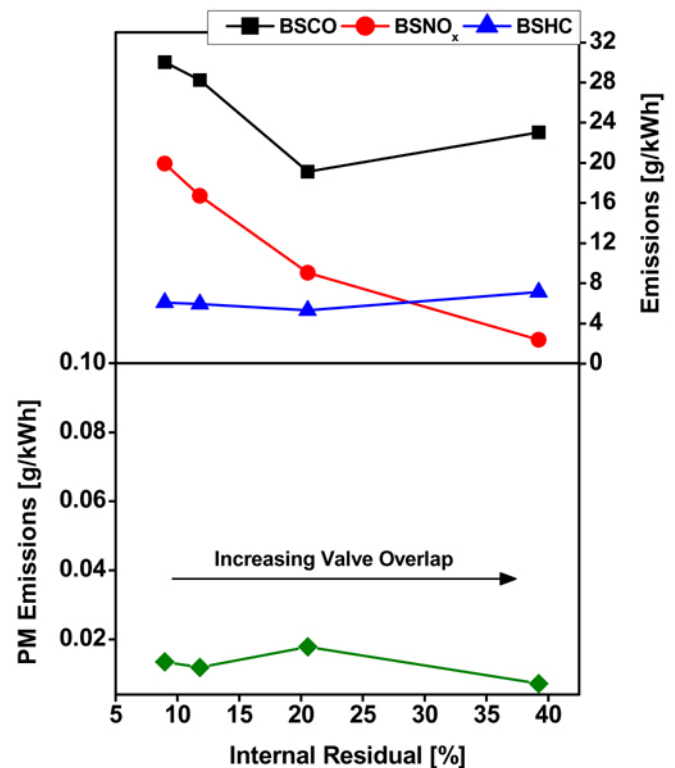


Figure 4. The effect of increasing burned gas residual on exhaust emissions levels.

The results in Figure 4 show that increasing iEGR serves to reduce three of the four primary pollutants examined in this study. The effect of iEGR on PM is less clear than other exhaust components, primarily because the level of PM from the engine was very near the limit of the measurement technique to resolve. While extremely long sampling times may have improved the resolution, the program schedule and other hardware constraints made those impracticable. However, the general trend appears to be that increasing

levels of iEGR serve to reduce the level of PM from the engine. Previous researchers, working on diesel engines, have reported that a combination of high EGR levels and increased pre-mixed combustion levels result in a reduction in the formation of PM emissions from these engines (see e.g. [16-17]). Their conclusion was that by reducing the combustion temperatures, the formation of soot, even from rich regions, can be reduced or functionally eliminated. In a gasoline engine, the combustion mechanism is not a diffusion flame, so the presence of rich regions is substantially reduced in comparison. However, improper mixing can result in locally rich areas in the combustion chamber, particularly in GDI engines (see e.g. [9, 11, 22-23]), but also in their PFI variants. In addition, both PFI [24] and GDI engines [2, 3, 4, 9, 13] have been shown to form liquid films in the combustion chamber during the intake stroke that persist until after combustion, leading to increased HC and PM emissions. Unfortunately, this reduction in combustion temperatures, while beneficial for reducing the formation of PM and NO_x, also can result in increased HC emissions (see the results in Figure 4 and [25-26]). This is a particular problem at the lightest loads, where increasing the residual levels past a certain point (more than ~ 35% internal residual) can decrease the post-flame temperatures enough to cause a significant increase in HC emissions despite the engine continuing to demonstrate stable combustion.

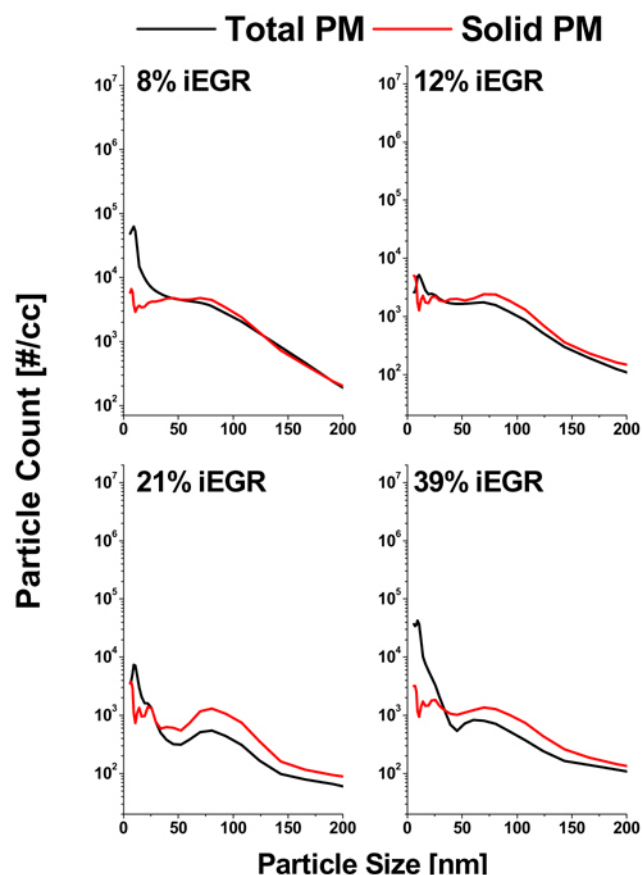


Figure 5. The effects of internal EGR on particle size and count at 2000 rpm / 2 bar bmep.

Since one of the proposed regulations on PM emissions from gasoline engines is number count, measurements of the size distribution and particle count were made at this condition also. The measurement differentiated between total PM and solid PM, with the solid PM being particulates whose volatile components have been stripped using an oxidation catalyst, similar to the conditions in the tailpipe of a gasoline engine. In some instances, the measured count of solid PM is larger than the measured count of total PM, which may be the increased path length that the sample has to traverse leading to increased agglomeration of the smaller particles into larger ones. However, the results for this low load condition, shown in Figure 5, show that the addition of EGR serves to decrease the number of smaller particles as well as the overall particle mass (Figure 4), which is important since the smaller particles (PM with size less than 2.5 μm) are of particular interest to regulators. The presence of increased volatile components at high EGR levels is indicative of the decreased combustion temperatures leading to less solid PM and more condensed volatile components, which are removed in the catalyst or, when examined pre-catalyst, can show up as unburned HC emissions in the heated sample line.