

Effect of EGR on Particle Emissions from a GDI Engine

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ABSTRACT

Gasoline direct injected (GDI) engines are becoming a concern with respect to particulate matter (PM) emissions. The upcoming 2014 Euro 6 regulations may require a drastic reduction in solid particle number emissions from GDI engines and the proposed California Air Resources Board (CARB) LEV III regulations for 2014 and 2017 will also require some PM reduction measures. As a result, it is necessary to characterize PM emissions from GDI engines and investigate strategies that suppress particle formation during combustion. The main focus of this work was on using exhaust gas recirculation (EGR) as a means to reduce engine-out particle emissions from a GDI engine with an overall stoichiometric fuel to air mixture.

A small displacement, turbocharged GDI engine was operated at a variety of steady-state conditions with differing levels of EGR to characterize total (solid plus volatile) and solid particle emissions with respect to size, number, and soot or black carbon mass. Cooled external and un-cooled internal EGR were both investigated to provide further insight into the role of bulk temperature on PM formation. Analysis of the data helped to identify the dominate mechanisms that contribute to particulate emissions in GDI engines at different operating conditions and determine what EGR strategies would be most effective at reducing engine-out particulate matter.

In general, cooled external EGR was very effective in reducing soot mass by as much as 65 percent, compared to engine baseline. Solid particle number followed the soot mass trend, but showed an opposite trend for some engine operation. These findings present some complexity in achieving both soot mass and solid particle number reduction with one strategy. Internal EGR was much more effective than cooled external EGR in reducing soot mass and solid particle number at light load, low temperature combustion. EGR increased engine-out volatile particles that are mainly formed during dilution and cooling of

hot exhaust. Other work showed that a three-way-catalyst can be very effective in reducing the precursor of volatile particle formation.

INTRODUCTION

As fuel economy and emissions standards evolve and become more stringent, engine and vehicle manufacturers must continually refine the dominant design of the port fuel injected (PFI) gasoline engine in order to meet these regulations. Unfortunately, the flexibility for advanced fuel management and combustion strategies is approaching an inherent design limitation for port fuel injection as companies seek to improve fuel economy. These limitations prompted several engine manufacturers to develop and introduce GDI engines over the past decade, with the intent of creating a platform with the capability to meet current and future fuel economy regulations. With the increased implementation of the GDI engine, PM emissions have become a source of concern for the gasoline industry [1]. Several studies have been performed to understand the mechanism by which GDI systems yield increased PM and/or HC emissions [1, 2, 3, 4, 5, 6]. In general, GDI engines have elevated PM emissions due to non-homogenous mixing and the presence of localized rich fuel to air mixtures in addition to liquid fuel in the combustion chamber, which has been extensively documented by multiple researchers [2, 7, 8, 9, 10, 11, 12]. This is particularly relevant since the Euro 5 light-duty emissions standard has 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 [12], with expectations that future regulations will constrain gasoline-fuelled engines. Furthermore, GDI engines Euro 6 solid particle number (PN) regulation is anticipated as being the next hurdle for manufacturers to overcome, but the PN level has not been agreed upon yet. Previous work has been successful in utilizing EGR, both un-cooled and cooled, to reduce PM mass and other regulated emissions while improving fuel economy [13, 14, 15, 16]. However, there is

limited published research on the topic of characterization of PM mass and PN as it relates to GDI engines utilizing cooled EGR as an emissions control strategy.

The focus of our research was on the effect of cooled external EGR and internal EGR on GDI engine-out soot mass emissions and on total (solid plus volatile) and solid particle size and number. Internal EGR is essentially in-cylinder trapped exhaust gases whereas external EGR is collected from the exhaust system and reintroduced into the engine air intake. Soot mass was measured with an AVL microsoot sensor (MSS), and particle size and number were measured with a TSI engine exhaust particle sizer (EEPS). Solid particle size and number measurements were facilitated with the use of a solid particle sampling system (SPSS)

EXPERIMENTAL SETUP

A 1.6L GDI Prince engine was utilized for all test work as it provided an acceptable representation of modern European passenger car engines. However, to maintain high specific power output with high levels of EGR (25%+), the base engine was modified to include a high energy, long duration ignition system and an advanced multi-stage boosting system. Testing consisted of operating the engine at several steady-state speed and load conditions, performing a constant power sweep at various speeds, and operating in fuel enrichment regions of the engine map, all while varying the amount of EGR. Engine performance and exhaust emissions were measured at the following operating conditions:

- 1) Mid speed, light load (2000 RPM 2.0 bar BMEP)
 - a. Internal EGR sweep provided by intake and exhaust valve event overlap
 - b. Cooled external EGR sweep (0-20%)
- 2) Mid speed, mid load (2500 RPM 6.7 bar BMEP)
 - a. Cooled external EGR sweep (0-25%+)
 - b. GDI start of injection sweep
- 3) High speed, mid load (3500 RPM 9.6 bar BMEP)
 - a. Cooled external EGR sweep (0-25%+)
- 4) Constant power sweep (16kW)
 - a. 1250, 1500, 2000, 3000 RPM
 - b. With and without cooled external EGR
- 5) High power enrichment region (3000 RPM 16 bar BMEP)
 - a. Cooled external EGR sweep (0-25%+)
 - b. Equivalence ratio sweep (stoichiometric to 1.3)

These operating conditions were selected because they are representative of down-speed engine operation on a FTP 75 and US06 drive cycle ('down-speed' is a concept promoted by

many engine manufacturers as a method to increase fuel efficiency, by operating the engine at lower speeds to reduce friction as well as operating at a higher BMEP to reduce pumping losses, for future CAFE or CO₂ standards)[17,18]. The constant power sweep was selected to represent a high-speed highway cruise condition where an additional transmission up-shift is often employed for fuel economy. Downsized and boosted engines (e.g. 1.4L turbo to replace 2.4L naturally aspirated (NA) engine) offer a fuel economy benefit primarily at low loads (where most drive cycle operation occurs) [6], but for the vehicle to retain adequate drivability the engine must provide higher specific power output. Fuel enrichment is often employed at very high specific power levels to mitigate engine knock and excessive exhaust temperatures. Recent work has shown [19] that fuel enrichment with external EGR greatly reduced total and solid particle number and mass emissions from a PFI gasoline spark ignited engine, compared to a similar operation without external EGR. Similarly for the GDI engine in this work, an engine speed of 3000 RPM with 16 bar BMEP was selected to investigate the effect of enrichment on PM emissions with and without external EGR. High levels of EGR are capable of eliminating the need for fuel enrichment and this investigation quantified the impact on particle emissions.

All emissions were measured on an engine-out basis and no catalyst was present in the exhaust system. A Horiba Mexa 7100DEGR 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 engine exhaust. Soot particle mass was measured continuously in real-time with an AVL 483 microsoot sensor and AVL Exhaust Conditioning unit set to dilution ratio of 3. The soot sensor uses a photo-acoustic principle for measurement by exposing the exhaust gas to a modulated laser beam. The soot particles strongly absorb the pulsating light and will heat the gas surrounding it, creating sound waves that are detected by the systems microphones. This method provides a typical detection limit of 5 µg/m³. Particle count and size were measured with a TSI 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 covers a size range from 5.6 nm to 560 nm with a resolution of 16 channels per decade. An aerosol stream enters the instrument through a 2.5 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 [10].

The EEPS analyzer was used downstream of a SPSS [12] that facilitates the measurement of total (solid plus volatile) or solid particle number concentration and size distribution. The SPSS is equipped with a two-stage dilution system that was set at a nominal dilution ratio of 25. It is also equipped with a heated oxidation catalyst to facilitate the measurement of solid particles [12]. The sample probe for particle measurement was placed in the exhaust facing the stream. It was designed to target isokinetic sampling at mid engine speed (2500 rpm) and load (6.7 bar BMEP). A dilution ratio of 4 was implemented at the exit of the sample probe before entering the heated oxidation catalyst. The residence time of the first dilution stage is about 1 second. The secondary dilution stage was set at a dilution ratio of 6 at the exit of the oxidation catalyst or when bypassing the catalyst. No correction for the size-specific concentration was implemented as the measured size-specific losses were less than 5% in the size range from 10 to 200 nm [12]. All four exhaust measurements (gas-phase emissions, soot mass, solid or total PM size and count) were conducted concurrently after the engine was given a 5 minute stabilization period. The two particulate matter analyzers were fully independent from one another using separate exhaust probes in separate locations. An overview of the general test setup is shown in Figure 1.

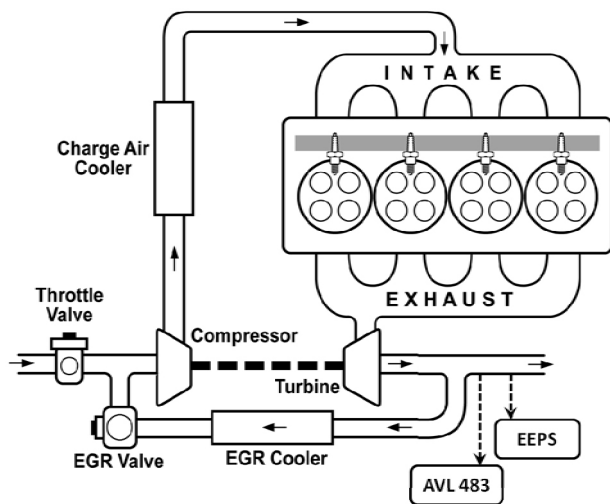


Figure 1. Engine and emission sampling layout

RESULTS AND DISCUSSION

The results section examines the impact of external and internal EGR on PM emissions measured during each type of test completed. The primary focus is on soot particle mass, particle count and size distributions expressed in brake specific quantities and concentrations however these two values should not be directly compared. During these tests, all

GDI parameters at a given speed load condition were held constant; there were no changes to fuel pressure or injection timing as EGR rate was manipulated. The GDI parameters were set to the OEMs recommended values for each operating condition with 0% EGR. The intake cam phaser was also fixed to the OEMs recommended location during the testing. The sensitivity of these values on PM/PN while operating with high levels of EGR was not explored during this study but might be an area of future research.

PART LOAD CONDITIONS

Downsized engines with reduced speed will operate at higher loads for a more significant amount of time compared to their NA counterpart in order to generate equivalent power levels. We represented these conditions at 2500 RPM and 6.7 bar BMEP, and 3500 RPM 9.6 bar BMEP with a stoichiometric fuel to air ratio and steady-state operation. At these conditions the engine was still partially throttled and the boost system was not engaged. The soot mass and solid particle count both decreased as EGR was added as shown in Figure 2. The magnitude was significant considering future US and EU regulations. EGR was capable of reducing brake specific soot mass by more than 50% and brake specific solid particle number by 38%, as shown in Table 1. Solid PN was determined by summing the counts over the detectable bins in the size range from 5.6 nm to 560 nm. Solid PN was not limited to a size window of any proposed regulation, but the majority of solid particles were in a size range greater than the EU 23 nm size limit, as shown in Figures 3 and 4.

The actual brake specific values for soot mass and particle number at both operating conditions are provided in Table 1 with the calculated percent difference between 0% and 25% cooled exhaust gas recirculation. In addition, the volatile fraction (VF), which is defined as the ratio of volatile particle number to total particle number, is provided. Large amounts of EGR reduced both volatile and solid particle number at 2500 RPM leading to a total particle reduction of 91%. However, at the higher speed condition, total particle number increased by almost 200% despite a 38% reduction in solid particle number. These results suggest that higher EGR consistently reduces soot emissions, but volatile particle emissions can be either higher or lower, depending on engine speed and load. Furthermore, the high VF observed at all operating conditions suggest that most of the particles emitted are volatile in nature. While volatile particle number emission is of great interest, it should be emphasized, however, that volatile particle formation and growth is subject to changes, depending on the exhaust dilution and cooling process [20]. More importantly, a three-way catalyst (TWC) was not used during this work to better represent volatile particle emissions from a typical engine exhaust configuration. Recent work [21, 22, 23] has shown that a TWC has little effect on solid particles and greatly reduces volatile particle formation and growth by oxidizing the volatile hydrocarbon precursor in the exhaust.

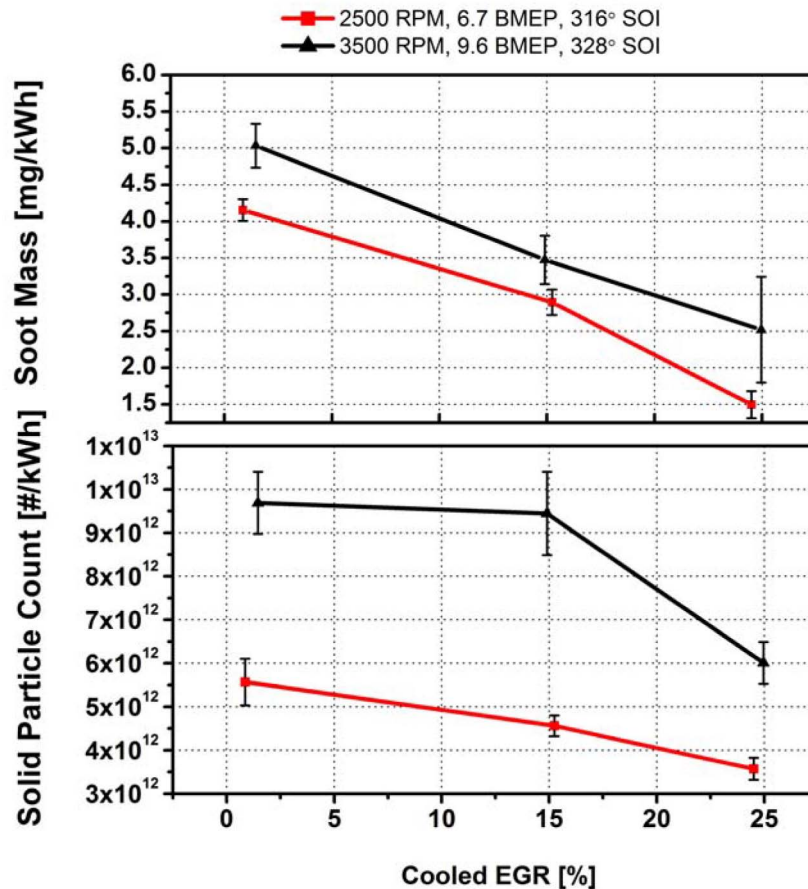


FIGURE 2. Soot mass and solid particle count during stoichiometric operation with increasing EGR.

TABLE 1. Percent change of soot mass and particle number during steady-state, stoichiometric operation with increasing EGR.

Operating Condition		Particle Number					Soot Mass	
	EGR Level	Volatile Fraction	Total	Change	Solid	Change	Mass	Change
	%		#/kW-hr	%	#/kW-hr	%	mg/kW-hr	%
2500 RPM, 6.7 BMEP 316° SOI, 5° bTDC	0	0.91	5.9E+13	-91	5.6E+12	-38	4.2	-64
	25	0.81	5.5E+12		3.5E+12		1.5	
3500 RPM, 9.6 BMEP 328° SOI, -5° bTDC	0	0.68	3.0E+13	198	9.7E+12	-38	5.0	-50
	25	0.93	9.1E+13		6.0E+12		2.5	

Figures 3 and 4 show total and solid particle size distributions at part load engine operation. For solid particles, the distributions fit a bimodal lognormal size distribution structure with a typical geometric standard deviation (GSD) of 1.4 and 1.6 in the nuclei mode and 1.5 and 1.7 in the accumulation mode. The geometric number mean diameter for the nuclei mode (NMD_{nuc}) was between 12 nm and 14 nm in diameter, and it was between 40 nm and 55 nm in diameter for the accumulation mode (NMD_{acc}). The EGR had minimal influence on the nuclei mode solid particles but resulted in an 8 nm reduction in the NMD_{acc} where most soot particles reside.

Reduction in solid particle size and number with EGR explain the reduction in particle mass observed in Figure 2. Also, it is worth noting that engine speed had an effect on the solid particle size distribution. The NMD_{acc} at 3500 RPM was about 7 nm smaller than that at 2500 RPM. One possibility for the reduced particle size is the reduced time for particle coagulation at higher engine speed. However, the low level of solid particle number shown in Table 1 does not support this hypothesis, as it would require a much longer time than the time differences in engine speed to shift the size distribution to a higher NMD_{acc} . For example, the brake-specific solid particle number shown

in Table 1 corresponds to an exhaust concentration of one to two million particles per cubic centimeter. It will take about 4 hours for the NMD_{acc} at this concentration to double [24], and certainly it will take much longer than the residence time between 2500 rpm and 3500 rpm to change by 7 nanometer. Another possibility could be that smaller primary particles were produced at 3500 RPM, compared to 2500 RPM. This hypothesis is supported by the fact that although there was less time at the higher engine speed for particle coagulation, the solid particle number concentration was higher and the NMD_{acc} was smaller, compared to the 2500 RPM case. Additional work will be needed on particle morphology to establish a more solid foundation for the above hypothesis.

As for the total particle size distributions, they exhibited a similar size distribution bimodal structure, GSD and GNMD

to that of the solid for the 2500 RPM, no EGR, and 3500 RPM, with EGR. However, volatile particles dominated the nuclei mode, in contrast to the domination of the accumulation mode for solid particles. For the other two engine operating conditions, significant volatile particle formation and growth was observed with NMD_{nuc} similar to that of the accumulation mode. For example, at 2500 RPM, no EGR and 3500 RPM, with EGR, a monomodal size distribution was observed with a NMD_{nuc} of 16 nm and 37 nm, where more than 91% of the particles were volatiles. This explains the reduction observed with total particles for the EGR case at 2500 RPM and the increase for the case with EGR at 3500 RPM, as shown in Table 1. While volatile particles are expected to be minimized with the use of a TWC, it is interesting to observe that there could be a room for combustion optimization where both the solid and volatile precursors can be minimized in combustion.

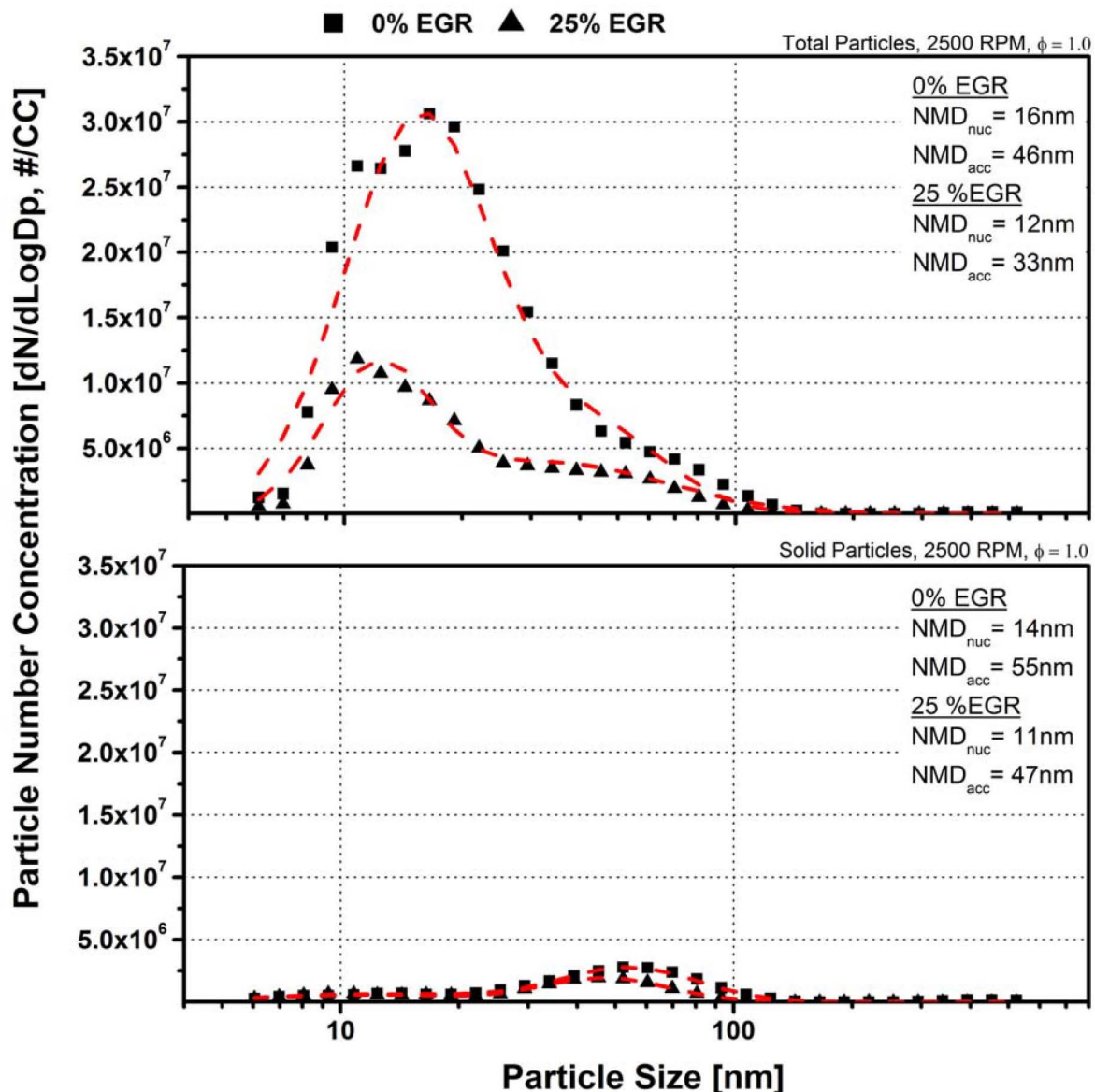


FIGURE 3. Engine-out total and solid particle number-weighted size distribution at 2500 RPM with increasing EGR.

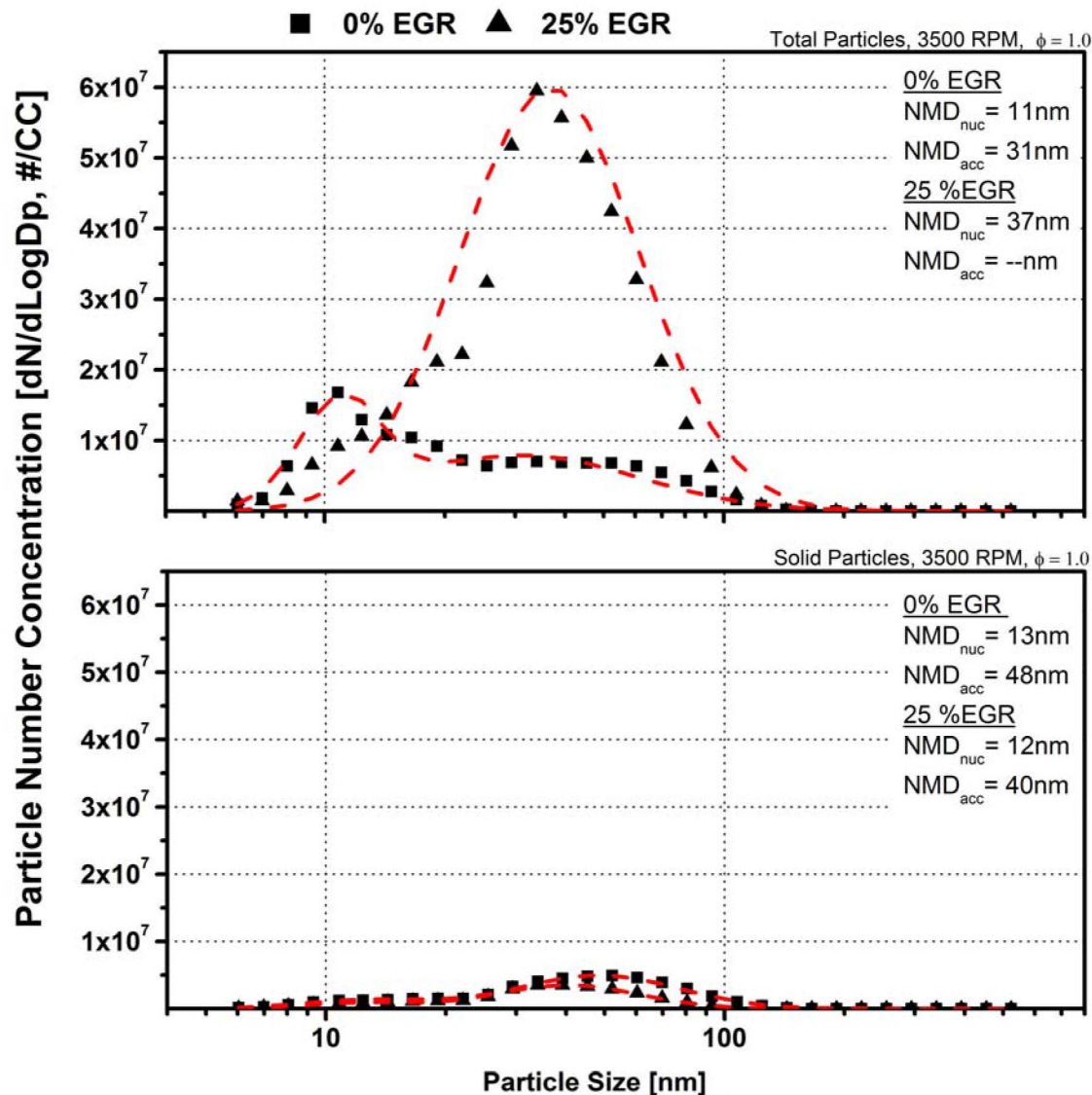


FIGURE 4. Engine-out total and solid particle number-weighted size distribution at 3500 RPM with increasing EGR.

16KW CONSTANT POWER SWEEP

A 16kW condition was investigated to represent highway cruising at a high vehicle speed. With modern transmissions moving toward more numerous gears or CVTs for fuel economy benefits, we looked at brake-specific particle emissions at different speeds. This testing was also able to indicate how EGR was impacting particle emissions. Particle emissions are the net result of formation, agglomeration, and oxidation. EGR is thought to impact all the stages, but the magnitude of each has not been quantified. As speed was changed, the GDI fuel injection parameters and intake valve opening timing were scheduled based on the OEMs recommended settings. Combustion phasing was held to MBT.

Consistent reductions of brake specific soot mass exceeding 50% were observed at every engine speed of the constant power sweep as well as modest reductions of solid particle count as

shown in Figure 5 as a result of increased cooled EGR. The 1500 RPM engine speed resulted in the most noticeable change in solid particle count with a 36% reduction. A summary of the total and solid particle number and soot mass changes are provided in Table 2. It has been observed by previous studies [1,25] that solid particle number and soot mass have the same trend. Figure 5 shows that the trend between solid number and mass may deviate depending on engine operating conditions. While the soot mass decreased at constant engine power with increased engine speed, soot particle number had an opposite trend. However, since this observation was based on two independent measurements (MSS and EEPS) it is important to investigate whether or not the two trends observed are consistent. In examining the reason for this behavior, it was found that the NMD_{acc} for solid particles was getting smaller as a function of increased engine speed, as shown in Figure 6, and similar to what was observed previously in comparing the