

Solid Particle Emissions from Vehicle Exhaust during Engine Start-Up

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ABSTRACT

Human exposure to vehicle exhaust during engine start-up can be encountered on a daily basis in parking lots, home garages, and vehicle stop/start traffic environment. This work is the first pilot study to characterize solid particle number and size distribution during engine start-up using various light-duty vehicles with different technology engines. A total of 84 vehicles were tested in this pilot study, consisting of post-2007 diesel engines equipped with high efficiency diesel particulate filters (DPFs) as well as modern gasoline port fuel injected (PFI) and gasoline direct injected (GDI) engines equipped with three-way-catalysts (TWCs). Particle concentration from DPF equipped diesel engines were found to be the lowest, while GDI and 8-cylinder PFI engines had the highest particle emissions. The average solid exhaust particle concentration observed with GDI engines during engine start-up was 12×10^6 part/cm³, this is a factor of more than 4000 higher than the ambient background concentration. A PN emissions index concept was developed to rank post 2010 model-year vehicles tested relative to a 4-cylinder diesel with DPF, used as the best available technology for low solid particle emissions. GDI engines had the highest PN indices, with up to a factor of 8000 higher for particles larger than 25 nm ($D_p > 25$ nm) and up to 900 times higher for particles smaller than 25 nm ($D_p < 25$ nm).

This study presents the differences seen in solid particle number emissions at engine start-up among the modern vehicle fleet. While all vehicles tested are expected to meet the respective emissions standard in the engine laboratory, there seems to be a drastic difference in their particle emissions performance in the real world under engine start-up. Lowering the PN emissions index from gasoline engines during engine start-up in future vehicles could be beneficial to the environment and the public as a whole. The priority should be on GDI engines followed by 8-cylinder PFI engines. High efficiency particle filters in engine exhaust such as diesel with DPF provides the best available technology for solid particle reduction, as shown in this work.

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INTRODUCTION

Passenger car engines are going through some drastic changes to meet the regulated emissions of NO_x, CO, NMHC, particulate matter and greenhouse gases such as CO₂, CH₄, and N₂O. This is in addition to the fuel economy regulations [1, 2, 3, 4]. To meet these requirements, diesel engines were equipped with a diesel particle filter (DPF) along with lean NO_x trap or urea SCR in 2007[5]. Gasoline engines are shifting from the widely used port fuel injected (PFI) engine toward the gasoline direct injected (GDI) engine for fuel economy benefits [6, 7]. GDI engines are known to emit higher particle emissions than PFI engines. Furthermore, engines that don't have active exhaust emissions control for particle emissions reduction such as an exhaust particle filter are likely to emit particles to the atmosphere in various degrees due to engine operating condition and weather conditions [8, 9]. One such operation is engine start-up.

Engine start-up is a common event that occurs multiple times on a daily basis. It takes place in home garages, and parking lots of many different places such as shopping centers, malls, grocery stores, schools, etc. Furthermore, engine start-up occurs multiple times in a hybrid vehicle drive to provide assistance to electric motor and/or for

battery charging. In addition, due to the high interest in fuel economy savings, multiple engine start-ups are expected to take place in traffic jams and at stop lights, where the engine in a vehicle will completely stop during traffic and start again when needed. It is evident that human exposure to engine exhaust during engine start-up can be encountered multiple times during a normal day. Thus, it is important to characterize particle emissions from vehicles during engine start-up for different technology engines representing the modern vehicle fleet. Such information can shed some light on the magnitude of this issue and helps differentiate different engine technologies that provide a better particle emissions control. This work includes the characterization of solid particle number and size distribution under engine start-up from a total of 84 passenger cars and light-duty trucks. The engine technologies included diesel with DPF, port fuel injected (PFI) and direct injected (DI) gasoline with three-way-catalysts. Real time ash particle measurement was conducted for some limited number of vehicles. The work was conducted in the parking lots of the University of Texas San Antonio (UTSA) and Southwest Research Institute. All vehicles were available for testing on a voluntary basis by their own drivers. The testing was done during the summer months with an ambient temperature of about 35°C.

EXPERIMENTAL SETUP

Establishing a correct methodology and engineering a dilution system that is capable of significantly diluting raw exhaust with well characterized solid particle loss down to 15 nm was needed for this study. Commercial dilution systems may be used if available, but may not provide the flexibility needed on this project. A dilution system that dilutes the sampled exhaust was developed for use in this project. The system was designed with flexibility to be used in the field and with high and low dilution to accommodate particle instrument normal range of operation.

Solid particle measurement occurred via a probe placed in the outlet of the tailpipe of a vehicle. The exhaust was heavily diluted in the 1st stage of the dilution system and then routed to a catalytic stripper that eliminates volatile (gas) phase particle precursors, letting through only solid particles for measurement. To develop a characterization of PM emission from various vehicles, instruments capable of measuring real time (second by second basis) number concentration and size distributions were chosen. Particle measurement instrumentations such as the Engine Exhaust Particle Sizer (EEPS) and Condensation Particle Counter (CPC) were utilized for this study. However, a complete data set was recorded only with the EEPS instrument, thus the size and number concentration data reported in this paper were only from the EEPS using the original instrument algorithm provided by TSI, assuming spherical particles. Limited data were reported with an ash measuring instrument that is described in the procedures section.

Dilution System

Two different concepts capable of diluting vehicle exhaust were employed in this study. The system with the least losses and ease of use was selected to be used for the actual experimental work. For each system, a sample probe would draw an exhaust sample from the tailpipe of a car and transport it to the inlet of the dilution system via a heated sample line. The transport line from the sample probe to the inlet was heated at 150 °C to eliminate moisture from the sample. Refer to Figure 1 for a schematic outlining the primary section of the dilution system. An ejector pump was placed downstream of the inlet to drive the flow through the long sample line. The ability of the ejector pump to create a vacuum is made possible by compressed air flowing through a small circular opening to generate a high velocity. This air expands, resulting in decreased pressure to provide vacuum levels up to 27.5" Hg. Most of the sample exits the system at this point via the bypass facilitated by the ejector pump. The remaining sample passes through a 0.0471 in diameter orifice; passing the sample through the orifice with pressure transducers and thermocouples enabled the calculation of the sample flow rate (the flow rate of the initial exhaust sample entering the system).

The entire section from the sample inlet to upstream of the catalyst was heated and maintained at 150 °C. An ejector pump was placed downstream of the orifice to introduce the first stage of dilution (the primary stage). It is important to note that the dilution air provided to the entire system was compressed air which was routed through an air dryer and HEPA filter before entering the system. This process ensured that the incoming air was free of moisture and particulates.

The mixture of sample and diluted air was then routed through an oxidation catalyst (at 300 °C). In 1995, Khalek and Kittelson [10] published on a CS for volatile particle removal. The CS consisted of a well characterized heated oxidation catalyst, along with a copper cooling coil tube. The purpose of the cooling coil was to cool the sample exiting the CS by convection down to ambient temperature level suitable for particle instruments. The CS's main purpose was to remove volatile particles and only penetrate solid particles for analysis. The same type of catalyst was used for the dilution system to remove volatile particles.

1st Concept - Use of Oxygen Sensors to Measure Dilution Ratio for Secondary Dilution

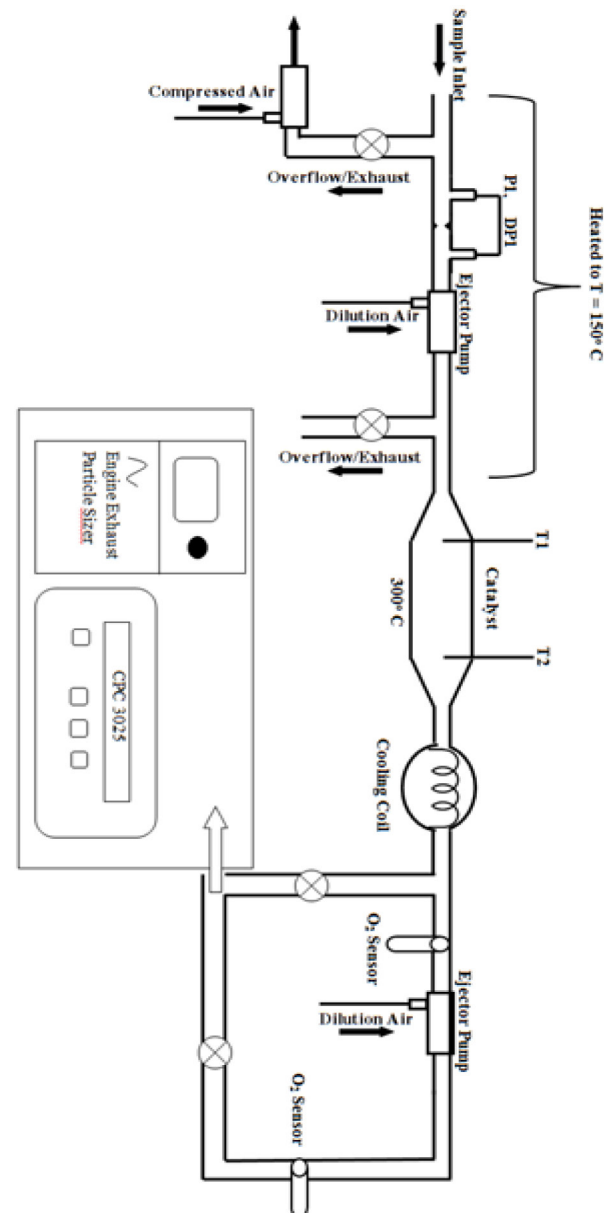


Figure 1. Concept 1-Use of Oxygen Sensors for Secondary Dilution

The intent behind concept 1 (Figure 1) was to use oxygen sensors as a quick way of detecting the dilution ratio through the second stage of the dilution system. Providing dilution with nitrogen enabled the

oxygen concentration to decrease in between the first and second oxygen sensors. Since both oxygen sensors were calibrated synchronically and a linear curve fit was obtained, it was assumed that the detection capability and performance would be the same for both sensors. The decrease in the oxygen concentration between the two sensors was a quick way of detecting the amount of dilution being provided. A stainless steel tubing line (greater than 10 times the diameter) was attached downstream of the secondary dilution to ensure proper mixing and correct computation of the dilution ratio. The sample then was routed out of the dilution system and into the sampling instruments for particle number and size detection.

Loss Checks

The dilution system mentioned in concept 1 was characterized using solid particles of 15nm, 20nm, 30 nm, 50 nm, and 100 nm in diameter. At each particle size, a dilution ratio of 14 for the primary section (where sample flow was 1 slpm) and 7-10 for the secondary section was used. The total dilution (primary*secondary) was maintained between 100 and 140. The dilution ratio (DR) is defined as:

$$DR = \frac{\text{air flow} + \text{sample flow}}{\text{sample flow}} \quad (1)$$

At each particle size and each section (primary/secondary), continuous sampling of solid soot particles was carried out for 5 minutes. The soot particulates used for the loss check study were generated from a miniCAST [11] soot generator coupled with a catalytic stripper. A Scanning Mobility Particle Sizer was used to size classify the soot particles [12]. Two calibrated CPC 3025A [13] were used; one upstream and one downstream of each dilution section to detect particle losses. The methodology used in this study for the dilution system loss characterization is analogous to that used by Khalek and Bougher in Development of a Solid Exhaust Particle Number Measurement System (2011); refer to Solid Particle Penetration section in the latter SAE published paper [14]. Particle loss checks were conducted separately for the primary and secondary systems mainly to characterize where (which section) had the higher losses. Particle loss (PL) is defined as:

$$PL = \frac{1 - (C_a * DR)}{C_b} * 100 \quad (2)$$

Where, C_a is the concentration of particles measured after dilution, C_b is the concentration of particles measured before dilution and DR is the dilution ratio. According to Figure 2, it is evident that the particle losses through the secondary stage were significantly high. The high losses would mean less particle penetration, especially small particles. Figure 2 shows that the losses for concept 1 dilution system increased as the particle size decreased, mainly due to particle diffusion. The higher particle losses in the second stage of dilution, however, can be attributed to thermophoretic loss caused by the heated

oxygen sensors which heat up during normal operation to 600°C. Due to the rise in temperature by the heated oxygen sensors, the sample temperature increased and then experienced cooling downstream of the oxygen sensors. Thus, particles passing through the secondary dilution route experienced more losses mainly due to thermophoresis [15]. According to the theory, particles suspended in a gas in which there exists a temperature gradient experience a net thermophoretic force in the direction of decreasing temperature. Due to this effect, particles deposit on the walls and thus lead to higher particle losses. Due to the high particle number losses, it was deemed necessary to make an alternation to this dilution system. The ejector pump in the secondary stage of dilution can also result in particle losses [16], but the primary dilution system also had a similar ejector pump with much less losses than the secondary. Thus, the ejector pump was not a contributor to the large differences observed between the primary and secondary stage of dilution.

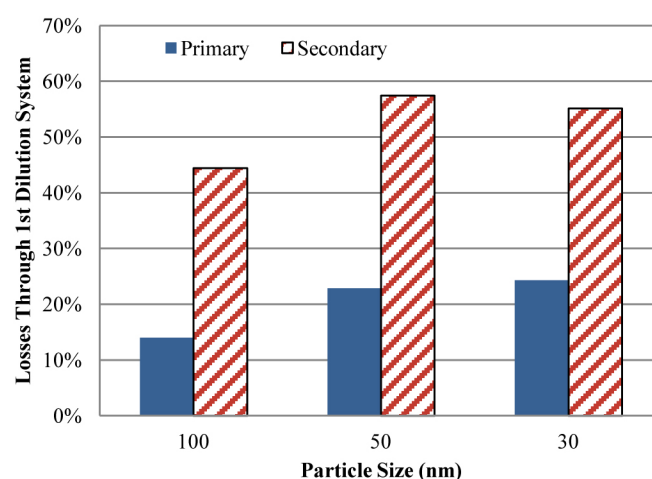
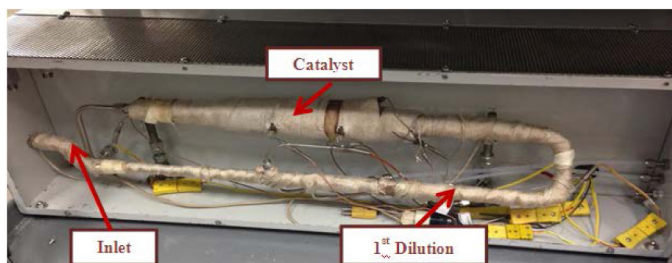
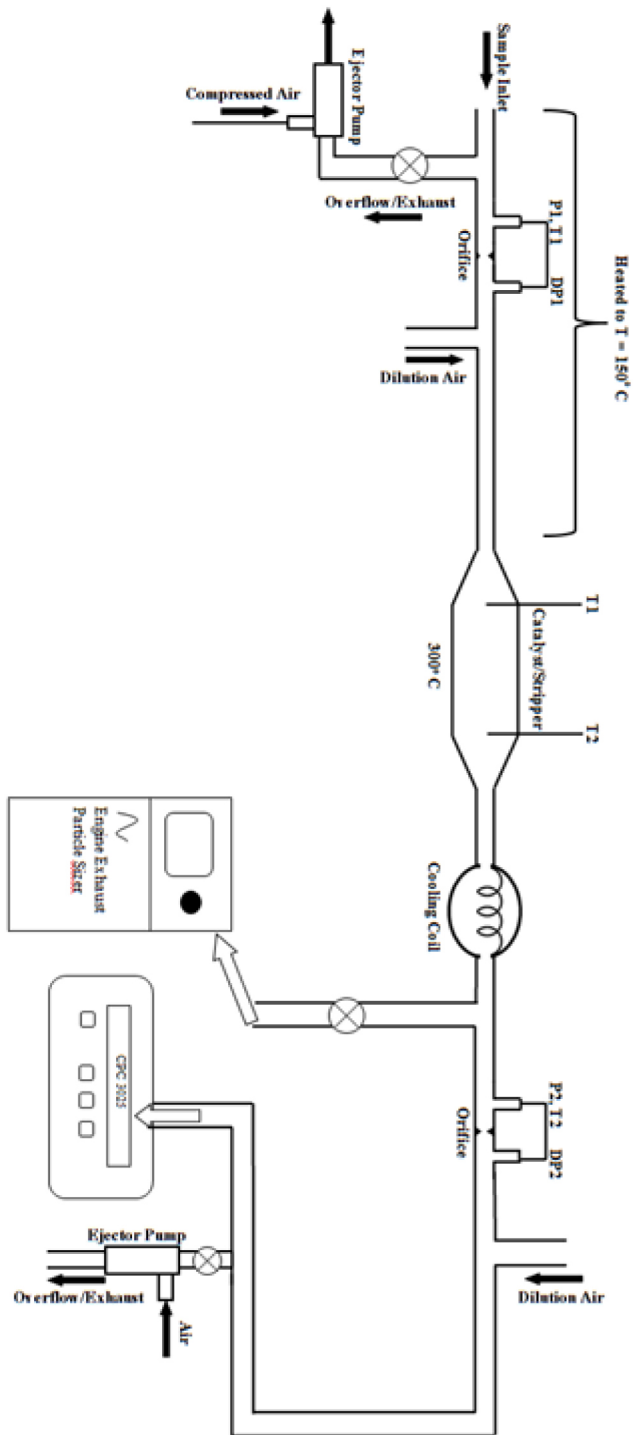


Figure 2. Particle Losses through 1st Dilution System

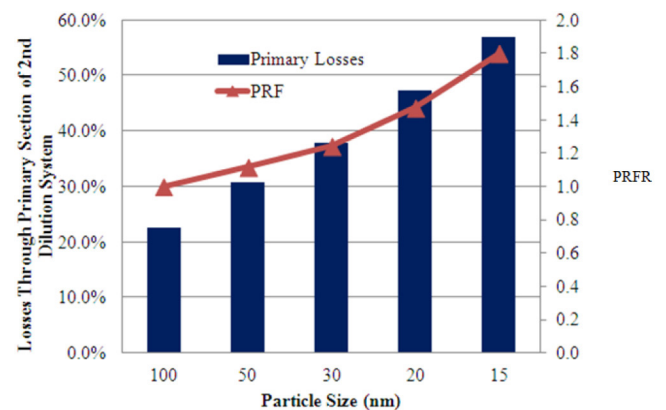
2nd Concept - Use of Orifice to Measure Dilution Ratio in Secondary Dilution

Despite the ease of use of oxygen sensors to derive an accurate dilution ratio, their inability to provide a lower particle loss led to the development of concept 2. Concept 2 eliminates the need of oxygen sensors by incorporating an orifice analogous to the one used on the primary section of the dilution system (Figure 3). Furthermore, the need of Nitrogen only dilution in the secondary was no longer needed, the sample could be diluted via regular compressed air. Figure 4 is a picture of the heated side of the dilution system along with the catalyst and Figure 5 shows the dilution and instrument sample ports. In concept 2, instead of ejector pumps, the EEPs and CPC instruments are used as the driving force for the flow. For the secondary dilution system, an ejector pump was used simply as a flow driver outside the sample line used for particle measurement. This flow driver helps drive the dilution air while the CPC helps drive the sample flow across the orifice.



The same loss check experiment described earlier was performed on the modified system, the results of which are plotted in [Figure 6](#). The use of the orifice to derive sample flow and dilution ratio reduced the losses from the secondary section of the dilution system significantly. The recorded losses through the secondary section were so low that they were within the percentage of error associated with the particle measuring instruments. The secondary dilution contains nothing more than regular stainless steel tubing for flow transport, an orifice with pressure and temperature ports, and introduction of additional dilution. Due to the simplicity of this process, particle losses in this section were expected to be very low. Experimentation verified this prediction and thus for computation of overall particle penetration through the dilution system, any secondary losses were neglected. The primary dilution particle losses were mainly due to diffusion and thermophoretic losses, especially in the cooling coil downstream of the catalyst as the temperature cools down from 300 °C to 25°C. The particle reduction factor ratio (PRFR) has been normalized to 100 nm. The PRFR is defined as the penetration at 100 nm (P_{100}) over the penetrations (P_d), where d is 15 nm, 20 nm, 30 nm, 50 nm, or 100 nm respectively.

An ideal system would have an average PRF ratio of 1.0, indicating “that the particle losses of the system are independent of particle size between 15 nm and 100 nm [14].



A loss check was also performed for the heated 15 foot sample line to be used for sample transport into the dilution system. The results of these losses are reported in [Figure 7](#). Since the sample line consists of only stainless steel tubing, the losses were expected to be minimal. The penetration through both, the dilution system and the sample line,