ABSTRACT

A study has been conducted to measure the particle number emissions from a current-generation 1.6-liter, Euro IV-compliant turbocharged Gasoline Direct Injection (GDI) passenger car engine. A fast-response particle size spectrometer was used along with a PMP-compliant particulate measurement system to measure the effect of various engine parameters on the particulate emissions during the New European Drive Cycle (NEDC).

Overall particle number is shown along with further analysis of the transient particle emissions. The cold start clearly affects particle formation with approximately 50% of the cumulative particle number being emitted within 200 seconds of the start. Even beyond 200 seconds, the particle number emissions fall as the test progresses and are generally consistent with increases in engine coolant temperature indicating that cold engine fuel preparation issues are contributing to the particle number count.

The data from the fast-response particle size spectrometer sampling directly from the exhaust showed very rapid increases in particle emissions during engine transients. Correlation with lambda was shown with rich lambda transients resulting in significant increases in particle emissions. Changes in other engine parameters, notably engine fuelling and spark timing, were also seen to affect particle number.

Particle size information was also analyzed at high frequency. This showed wide ranges in accumulation mode particle size over short periods of time with larger accumulation mode particles seen during higher load conditions and smaller particles seen at low load and idle. At times the accumulation mode exhibited two distinct peaks of both larger and smaller particles simultaneously suggesting two distinct mechanisms of accumulation mode particle formation.

INTRODUCTION

The proportion of gasoline vehicles operating with Gasoline Direct Injection (GDI) fuelling systems is steadily increasing due to the benefits in specific power output, fuel efficiency and fuelling control.

One reason for the significant benefits of GDI is the charge cooling effect of the injected fuel resulting in higher volumetric efficiency and improved knock resistance. The latter allows use of increased compression ratios leading to further improvements in efficiency and specific power output.
GDI technology also improves fuelling control, notably allowing lean stratified operation with further benefits in fuel economy through reduced throttling losses. Initially, GDI engines were principally developed to exploit the fuel economy advantages of lean stratified operation within suitable operating envelopes. However, the emissions control difficulties associated with lean operation have produced a trend for stoichiometric homogeneous GDI engines. These have been emerging into the fleet for several years now and are gradually replacing the older port-fuel-injected (PFI) gasoline technology.

Further improvements in fuel economy are possible through turbocharging the GDI engine, allowing still higher specific power outputs with further opportunities for engine downsizing (hence reduced throttling losses at part load). However, in the case of turbocharged GDI engines, the presence of a turbocharger upstream of the catalyst tends to delay catalyst light-off and therefore more aggressive catalyst heating strategies are required. Fortunately the enhanced fuelling control available with GDI technology assists with these aggressive catalyst light-off strategies through the capability of running multiple injections in a single cycle. This allows a degree of mixture stratification, where a small early injection can provide a lean homogenous mixture which is supplemented by a late injection immediately before ignition to give a richer mixture around the spark plug. This improves combustion stability allowing very late spark timings to be used, with very high heat output and low emissions [1,2].

Whilst GDI offers many advantages over PFI, there can be issues relating to fuel preparation, even with the intake-stroke injection strategies typically used in the case of homogenous GDI. These fuel preparation issues are due to the fuel spray impinging on the surfaces of the combustion chamber and the reduced time for fuel vaporization compared with previous technology PFI engines. One consequence of these fuel vaporization problems is that higher numbers of solid particles are commonplace from current production GDI engines compared with PFI [4,8].

European emissions legislation has also evolved: particle mass emissions legislation for Stage 5 GDI vehicles has been fixed to a level common with Diesel and a particle number limit has been introduced for Diesel-powered vehicles in Europe for Stage 5+. The Diesel particle number standard has come with specific requirements for measuring particle number - this has taken its name from the body which defined the techniques: the Particle Measurement Programme (PMP), and will be explained in more detail later.

To meet the requirements of the latest particle emissions legislation, engine designers and calibrators need better insight into the particle formation processes occurring in both GDI and Diesel engines. The fast-response particle size spectrometer is one type of instrument that can help fulfill this need: it gives particle size and number information at up to 10Hz, with a T_{95-05} response time of 200ms; the combination of size and number can be used to infer mass. Experiments have been conducted elsewhere using a range of particle measurement equipment on various vehicles with a view to characterizing the particulate emissions and their sources [8].

Engine exhaust particle size has also been the subject of previous research [11]. This continues to be of significant interest because the nature of the particles can be inferred from their size: nucleation mode particles (about 10-20 nm diameter) are formed from condensation of volatile material whereas accumulation mode particles (about 80-100 nm) are solid predominantly carbon-based products of combustion. The notion of a particle's "diameter" has also been the subject of much discussion [3,9,10]: the shape of nucleation mode particles being considered to be roughly spherical but particles from the accumulation mode being an amorphous string of smaller sub-particles.

Identifying these two very distinct modes is important because Europe's Particle Measurement Program (PMP) [4] protocol for particle number counting aims to remove the volatile nucleation-mode particles from the particle number measurement. This is achieved within a PMP-compliant measurement system by passing the sample through a Volatile Particle Remover (VPR). This consists of heating and dilution stages designed to vaporize the volatile material and dilute the sample to reduce the partial pressure of the volatile material sufficiently to prevent further nucleation. In contrast, the DMS500 fast-response size spectrometer [6] measures particles in both accumulation and nucleation modes and separates the two modes by running a real-time bimodal log-normal fit [7]. This allows an equivalent of the PMP solid particle count to be produced as well as simplifying data analysis in the case where large quantities of data are produced in a very short period of time. Figure 1 shows a screen-shot from the DMS500 showing a particle spectrum from an engine aerosol with the two modes identified by the DMS500 bimodal log-normal fit.

This paper shows particle results from a latest-generation Euro IV-compliant GDI vehicle. These emissions are measured using the PMP particle counting technique but also with a fast-response particle size spectrometer so that engine transients can be studied in detail and particle size information can be studied.

**APPARATUS**

The main items used for these experiments were:

- A production stoichiometric turbocharged GDI vehicle
- Froude-Hofmann chassis dynamometer and robot driver
• Cambustion DMS500 fast-response particulate size spectrometer (for particle size, number and mass measurement)

• PMP-compliant particle number measurement device consisting of a VPR and a TSI 3790 Condensation Particle Counter (CPC)

VEHICLE AND ENGINE
This vehicle was chosen for study because it represents latest-generation GDI technology. Broadly speaking, vehicles of this technological complexity and performance are produced by various vehicle manufacturers.

The vehicle was a production vehicle with no modifications and therefore the information available for this engine is limited to what was available in the public domain and what could be observed.

The engine runs a stoichiometric fuel injection strategy and is equipped with a variable inlet cam phaser.

From observation, it is clear that the injector is fitted in the intake side of the cylinder head in a side-mounted location - i.e. the axis of the injector is almost perpendicular to the cylinder axis.

The emissions system on this vehicle consisted of a close-coupled catalyst with two substrates, the first of which has a high cell density to aid rapid light-off. In this case, the production catalyst was hydrothermally aged for 15 hours at 950°C to simulate approximately 50,000 miles of vehicle operation.

INSTRUMENTATION
Sample points were fitted directly into the exhaust for engine-out and post-catalyst emissions (see Figure 2). The engine-out location was immediately after the turbo-charger (and therefore approximately 100mm upstream of the 3-way catalyst front face) and the post-catalyst sample point was approximately 100mm downstream of the rear face of the catalyst. A full-flow dilution tunnel was used.

The DMS500 has a built-in dilution system allowing sampling directly from the exhaust pipe. In this paper both dilute and raw measurements are shown.

The PMP system sampled directly from the dilution tunnel.

FAST-RESPONSE PARTICLE SIZE SPECTROMETER
These items are described along with various applications and technical references at www.cambustion.com but briefly: the DMS500 particulate analyzer provides particle size, number and mass measurement with a response time of about 300ms in this configuration, i.e. with a heated sample line, primary dilution and high-ratio secondary dilution systems to allow sampling directly from the raw exhaust gas stream.
PMP PARTICLE MEASUREMENT SYSTEM

The sample was conditioned as specified by the Particle Measurement Programme (PMP) [5]. This conditioning involved dilution with air using a variable ratio rotary diluter heated to 150°C. The diluted aerosol then passed through a tube heated to 300°C in order to vaporize volatile material before being cooled by a further dilution with clean air at a ratio of 10:1. The cooled dilute sample was then sampled by a TSI 3790 Condensation Particle Counter (CPC).

DYNAMOMETER FACILITIES

A Froude-Hofmann robot driver was employed to drive a New European Drive Cycle (NEDC) on a Froude-Hofmann chassis dynamometer.

DATA ACQUISITION

Data were generally sampled at 10 Hz. A separate data file was recorded at 1 kHz for injector drive signal and fast-response gaseous emissions.

Data was also logged from the vehicle ECU through the on-board diagnostic (OBD) port. The recorded channels were limited to spark timing and engine speed to maintain a reasonable data logging frequency.

EXPERIMENTAL

The vehicle was evaluated over several NEDCs with different test configurations. A robot driver was used for drive-cycle repeatability and rapid cooling was used between tests to increase experimental throughput. These techniques have proved previously to produce good repeatability and equivalence to an overnight soak with a human driver.

RESULTS AND DISCUSSION

OVERALL TAILPIPE PARTICLE NUMBER

![Figure 3. NEDC particle number results for PMP and DMS500 systems](image)

The European “PMP” standard for particle number is well-defined [4] and a PMP-compliant system was used within the dilution tunnel for these tests alongside the DMS500 system. Comparison of the two recorded cumulative number levels is shown in Figure 3. Note that the DMS500 log-normal fit was used in this case to isolate and reject the nucleation mode, giving an accumulation-mode particle count.

The two instruments are reasonably well-correlated, with the DMS500 showing approx 12% higher total particle number compared with the PMP system. This is reasonable agreement for two aerosol instruments and indeed differences in this range are expected between two PMP systems [4,13].

For contrast with the particle numbers in Figure 3, particle mass results for this vehicle are approx 2.8 mg/km, well within the Stage 5/ Stage 6 requirements of 4.5 mg/km.
It is interesting to note that most of the particle emissions occur towards the beginning of the drive cycle, with approx 50% of the particle emissions occurring in the first 200 seconds. During this period a rapid catalyst light-off strategy is used which might be expected to affect the particle formation processes, but looking more closely, it is clear that the gradient of the cumulative emissions trace continues to fall well beyond the completion of any catalyst warm-up strategy. Even comparing the period between 400-600 seconds with the period between 600-800 seconds (noting the repeating pattern of the drive-cycle), it is clear that particle emissions are generally falling. The authors assume that this is due to steadily increasing surface temperatures aiding better fuel vaporization and avoiding “pool fires” [12]. Figure 4 shows the engine coolant temperature for this vehicle over a NEDC. Whilst engine surface temperatures may differ from bulk coolant temperature, the coolant temperature trace is consistent with this hypothesis.

![Figure 4. Engine coolant temperature for this vehicle over a NEDC](image)

The results are now examined in more detail focusing on the cold-start region, which is the main contributor to the overall number emissions.

**Cold-start (0-200 seconds) emissions**

Figure 5 compares the instantaneous particle number rate (N/s) from the DMS500 and PMP systems, both sampling in the dilution tunnel. It is clear that there are significant variations during the transients, with increases in engine load during the accelerations resulting in a significant increase in particle emissions. The DMS500 tends to show slightly higher peaks, due to its faster response time, but mixing within the dilution tunnel in this case smears the signal.

![Figure 5. Transient particulate emissions for first 200s after cold start. Both measurements made in dilution tunnel.](image)

For closer analysis of the engine transients, the DMS500 sampling in the raw tailpipe exhaust is more appropriate (see Figure 6). In this case, the faster time response of the DMS500 is clear, as is the contribution of short-duration transients to overall particle number.

![Figure 6. Comparison of particle number measured by the DMS500 from raw exhaust with particle number measured by the PMP system.](image)

Using this information, it is then possible to establish correlation between engine parameters and particle emissions and improve our understanding of the particle formation mechanisms. For example, Figure 7 shows a comparison of engine-out Lambda and particle emissions over the 1st 100 seconds of the cycle. In this case, there is a general correlation between lambda and particle number. For example, there are two significant rich excursions associated with the 1st acceleration at 11 seconds and at 13 seconds which map directly on to significant spikes in the number count suggesting that, with better lambda control, significant savings in particle number could be obtained.
Figure 7. Comparison of engine lambda with particle number measured by the DMS300 sampling in the exhaust.

Note also in Figure 7 that the oscillation in lambda between 70s and 85s, caused by the closed-loop fuelling controller, is mirrored in the particle emissions trace, with richer lambda resulting in increased levels of particle emissions.

Another interesting feature in Figure 7 is the sharp increase in particulate emissions at 68s. This occurs during a steady-state cruise where such an abrupt change in engine-out conditions would not be expected.

To try to understand more about this feature, information about the engine operating parameters was analyzed. The information available was limited, given this was a production vehicle, but an OBD scan tool was available to record those engine operating conditions that were available. Direct measurements were also made of injector signals from one of the cylinders (cylinder 4) to identify the timing of the 1st injection and whether any split-injection strategy was being used.

Figure 8. Number of injections and engine speed during warm-up phase.

Figure 8 shows that, immediately after exit from crank and run-up, the engine operates a double injection strategy ("split-injection"), the intent of which is to create a rich kernel of gas around the spark plug and aid more stable combustion. This strategy continues until the second gear cruise at approximately 68 seconds, the same time that the increase in particle emissions occurs.

Figure 9. Spark timing and engine speed during warm-up phase.

However, it is not just the split-injection strategy which changes at 68 seconds, Figure 9 shows spark timing during the same period and it is clear that there is an abrupt increase in spark advance, associated with the end of the rapid catalyst warm-up strategy.

The simultaneous changes to spark timing and split injection strategy suggest that the catalyst heating mode is deactivated at this time. In this case, it is worth noting that there may be many more changes in engine parameters occurring simultaneously that we are not aware of (e.g. cam timing, injection pressure, etc). However, what is clear is that, in this case, the engine conditions occurring during the catalyst heating strategy result in lower particle emissions than the base engine calibration. With enhanced ECU access it would be possible to change these parameters to optimize the particle emissions during this cruise.

PARTICLE SIZE DISTRIBUTION

The transient particle size distribution is best viewed as a contour plot for timescales of 50 seconds or more. Contour plots covering the first 100 seconds of the NEDC can be seen in Figure 10.

From these contour plots it is possible to correlate spectral particle size changes with drive cycle events and to gauge the particle number emissions. This allows us to identify areas of the drive-cycle that warrant closer examination.

From the plots, the nucleation and accumulation modes can both be identified with some significant bursts of high number emissions in both modes; high nucleation mode particle numbers at the start (2 seconds) and high
Figure 10. Particle size and number concentration during the first 100 seconds of the NEDC.
accumulation particle numbers at the first acceleration (12 seconds).

Considering the accumulation mode in particular, there are significant size changes during the drive cycle, with the centre of its distribution varying from 50 nm to about 150 nm.

The plots also indicate the faint trace of an even larger mode at about 400nm. The number density of the particles within this mode is relatively low, but it is repeatable across several cycles and has been confirmed with other instruments. The authors suspect this may be from the burning of lube oil or perhaps artifacts of heavy gasoline fractions burning on engine surfaces.

Looking more closely at the second acceleration of the cycle (50-100 seconds), the change in particle emissions at the end of the catalyst heating mode is clear.

During its standard operation, the engine provides an opportunity to study moderate lambda changes and their effects of particle emissions by virtue of the closed-loop lambda control. Lambda oscillates between 0.97 and 1.03 and this “heating” at approximately 2 Hz can be detected within the particle contour plot. These moderate changes in lambda appear to affect particle number rather than particle size.

The DMS500 is supplied with data presentation tools which allow for detailed analysis of engine transient particle data and these tools have been used to zoom in on the first acceleration transient particle emissions which begins at 12 seconds.

The contour plot suggested that the accumulation mode size changes substantially during this acceleration and this is clarified in Figure 11 showing the peak accumulation mode size reducing from around 70 nm at 12.3 seconds to 40 nm at 12.8 seconds as its number concentration decays. The second burst of particles occurs at 14.8 seconds with its peak at about 130 nm.

It is interesting to note that the size spectrum at the 14.8 seconds time slice in Figure 11 has an irregular shape, as if both smaller and larger particles are occurring simultaneously. Analysis of the subsequent spectra (see Figure 12) shows the accumulation mode separating into two distinct peaks, at approx. 40 nm and approx. 130 nm. The presence of these two modes can be observed frequently throughout the cold-start region, well beyond the catalyst heating phase, and is most noticeable under higher load conditions.

The presence of two clearly separate modes suggest two distinct, spatially and/or temporally separate, mechanisms of particle formation. At times, either the larger or the smaller particles are seen, but at other times they coexist. The morphology of these particles is unclear, but it is assumed that they are carbon-based.

The authors took care to establish that the changes in accumulation particle size and the splitting of the accumulation peak were not caused within the primary sampling/dilution system of the DMS500 used when sampling the raw tailpipe exhaust gas. This was done by comparing the results with those recorded by the DMS500 within the dilution tunnel where no primary dilution was required (see Figure 13). In this case the two modes are still clearly present. Whilst the data shown in Figure 13 on its own could be explained by mixing of the temporally separate large and small particles in the dilution tunnel, the combination of this and the raw exhaust measurements are convincing - i.e. the two modes of accumulation mode particle formation can occur simultaneously and that this is not an artifact of the dilution conditions experienced in the instrument.

CONCLUSIONS

Particle number emissions have been measured from a late-generation GDI turbocharged vehicle using the PMP solid particle counting technique and using a fast-response particle size spectrometer. Overall particle number over the NEDC was circa $2 \times 10^{12}$ N/km.

From analysis of the measurements made, it is clear that particle emissions were a strong function of the cold start, with a large fraction of the particles being emitted within 200 seconds of the start of the cycle. Some of this could be explained by specific measures taken within the ECU strategy to light-off the catalyst quickly but, even beyond the catalyst heating phase, there are gradual but significant reductions in particle emissions as the cycle progresses. It has been suggested that this is consistent with engine warm-up and specifically the increase in temperature of engine surfaces resulting in improved fuel vaporization.

The use of a fast-response particle size spectrometer measuring in the raw exhaust has shown highly transient cold-start particle emissions, with abrupt "spikes" in solid particles occurring during engine transients through the cold-start period. The signals measured in the dilution tunnel were affected by mixing and did not show such a high frequency response. The spikes measured with the DMS500 showed strong correlation with rich lambda transients during higher load conditions. The influence of lambda on particles is perhaps unsurprising but this illustrates clearly the importance of ECU calibration/ control strategy actions to minimize particle emissions and the role that fast-response particle size spectrometers can play in the calibration process. An abrupt increase in particle emissions was seen at the end of the catalyst heating phase, where a step-change in engine
parameters occurred. Changes to injection strategy and spark timing were seen at this stage that might explain the increase in particle emissions, however, there may have been other changes scheduled by the ECU at the same time that could have contributed. In this case, extending the catalyst heating mode would have reduced overall particle emissions - at the expense of increased CO$_2$ emissions.

A wide range of accumulation mode particle sizes were seen with this engine, from 50 nm to over 150 nm mean particle size. In general the larger particles are seen at higher load. At times both larger and smaller particles were seen simultaneously. The presence of two distinct peaks in the spectrum, as opposed to a broad single spectrum, suggests two distinct spatially and/or temporally separate particle formation mechanisms. It has been speculated that the principal particle formation mechanism in this engine is incomplete vaporization of fuel leading to droplets of fuel being present during combustion, however, pool fires, caused by liquid fuel burning on surfaces within the combustion chamber, are known to result in increased particle emissions and may have a different particle size signature. In this case, it would be possible that the combination of these two particle formation mechanisms occurring simultaneously could result in the two separate peaks observed within the accumulation mode spectrum.

This hypothesis is conjecture and there is no independent evidence to support it at this stage. To help understand the particle formation mechanisms more clearly, and therefore inform engine design/calibration, additional information is needed. One analysis technique which could help is optical
analysis of the combustion event. This has been done previously to visualize pool fires [12]; the combination of this optical information with spectral analysis of the resulting particle concentrations might help to clarify the particle formation processes.

Whilst the mechanism is unclear, the wide variety of particle sizes seen with this engine is interesting - along with the observation of two distinct peaks in the accumulation mode. How representative this is of GDI engines in general is not clear, however, and similar tests on a range of vehicles would be helpful to identify how widespread these features are.

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