Issues Potentially Impacting the Measurement of PN during Regeneration of GPF and DPFs on Light-duty Vehicles

A Discussion Document for the PMP Working Group

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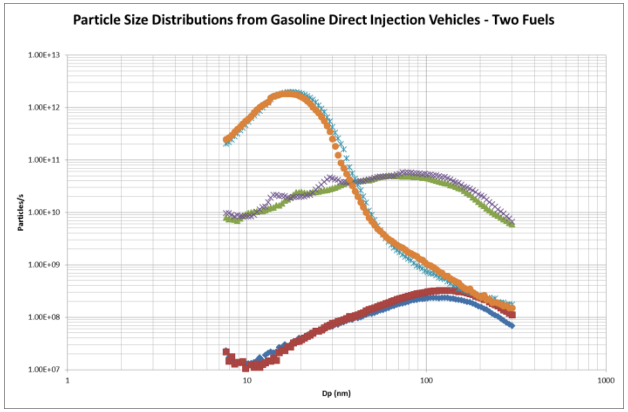

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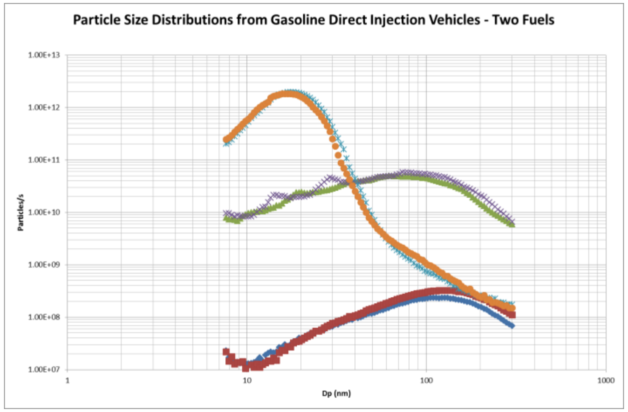
Approved

Contents and Introduction

- Part 1 – GPFs
- Part 2 – DPFs

- This document is produced to meet the following objectives regarding gasoline fuelled vehicles:
  - To identify key influences and issues likely to be encountered in procedures used to measure PN during active regenerations of diesel and GDI light-duty vehicles
  - To also consider potential issues with passive regeneration

Part 1- GPFs


Particle Size Distributions from Gasoline Direct Injection Vehicles - Two Fuels
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
Particles/s
1
10
100
1000
Dp (nm)

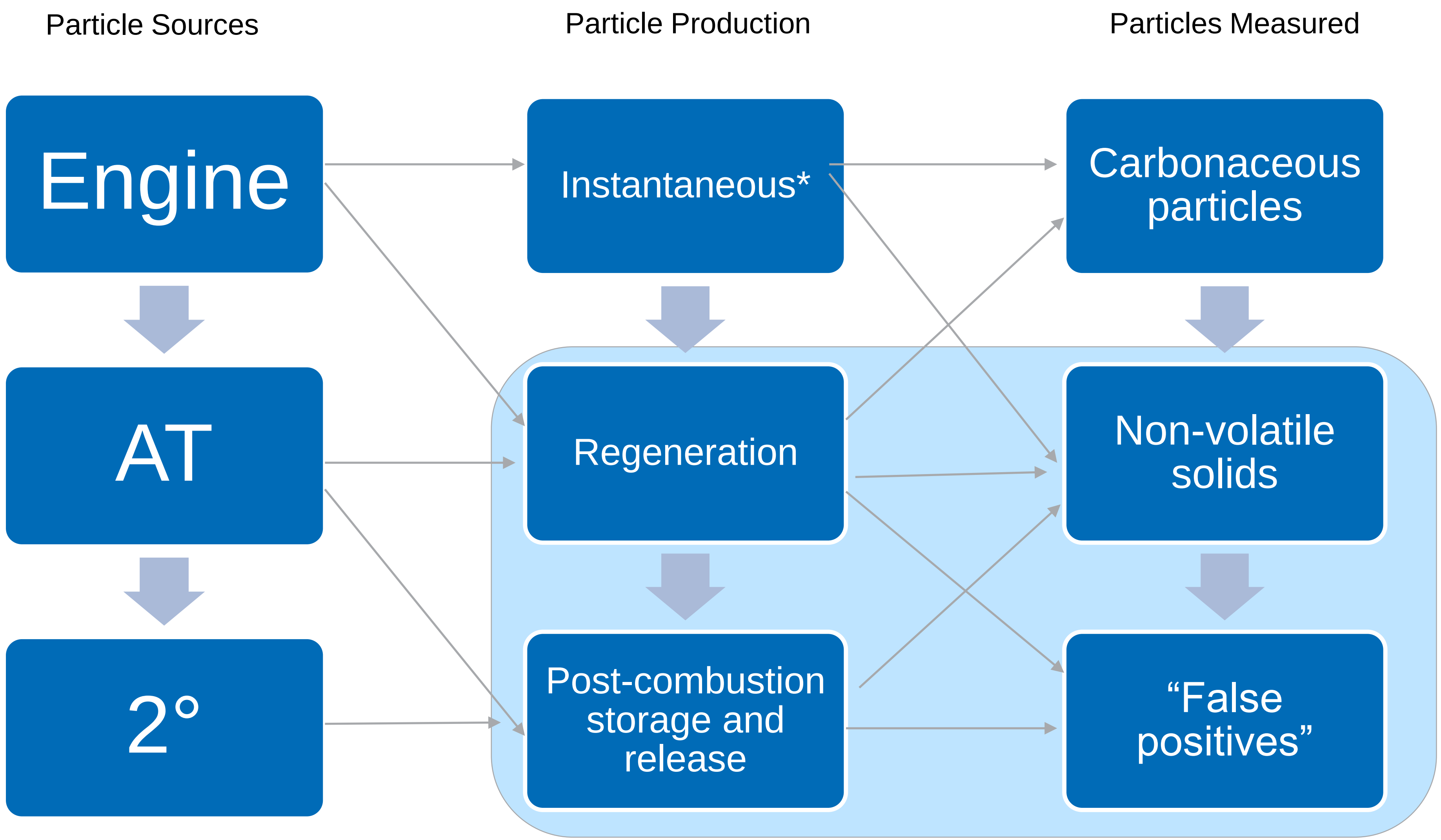
Contents – Part 1

- Particles from gasoline engines – sources and influences on regulatory procedures
- Possible GPF applications
- Gasoline DI – Regeneration Opportunities
- Regeneration Events and Effects
- General Impacts of Soot Combustion of the GPF
- Areas for Further Study

Introduction

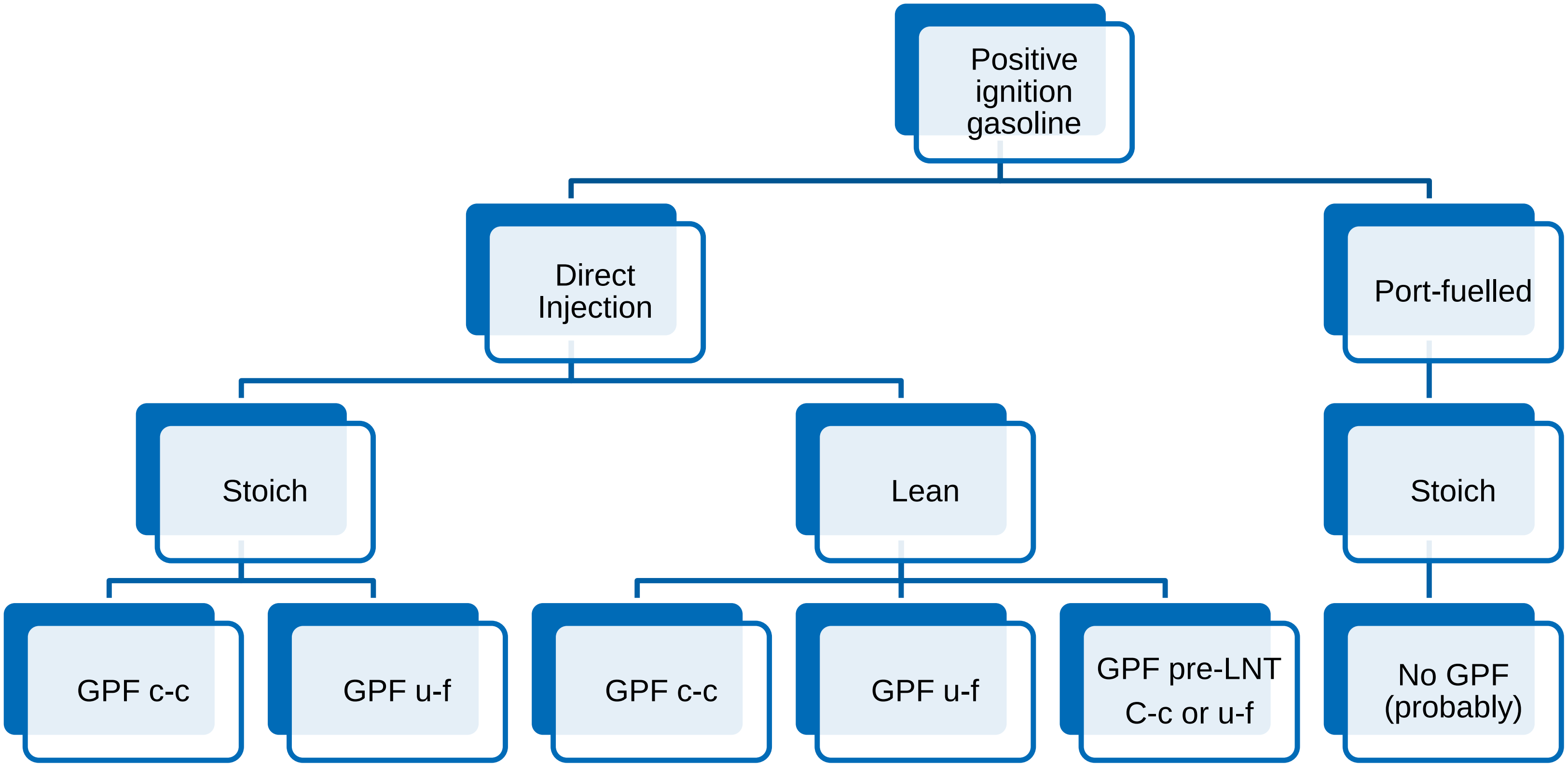
- The document is produced to meet the following objective regarding gasoline fuelled vehicles:
  - “To identify key influences and issues likely to be encountered in procedures used to measure PN during active regenerations of diesel and GDI light-duty vehicles.
  - Potential issues with passive regeneration will also be considered”

Particles from gasoline engines – sources and influences on regulatory procedures

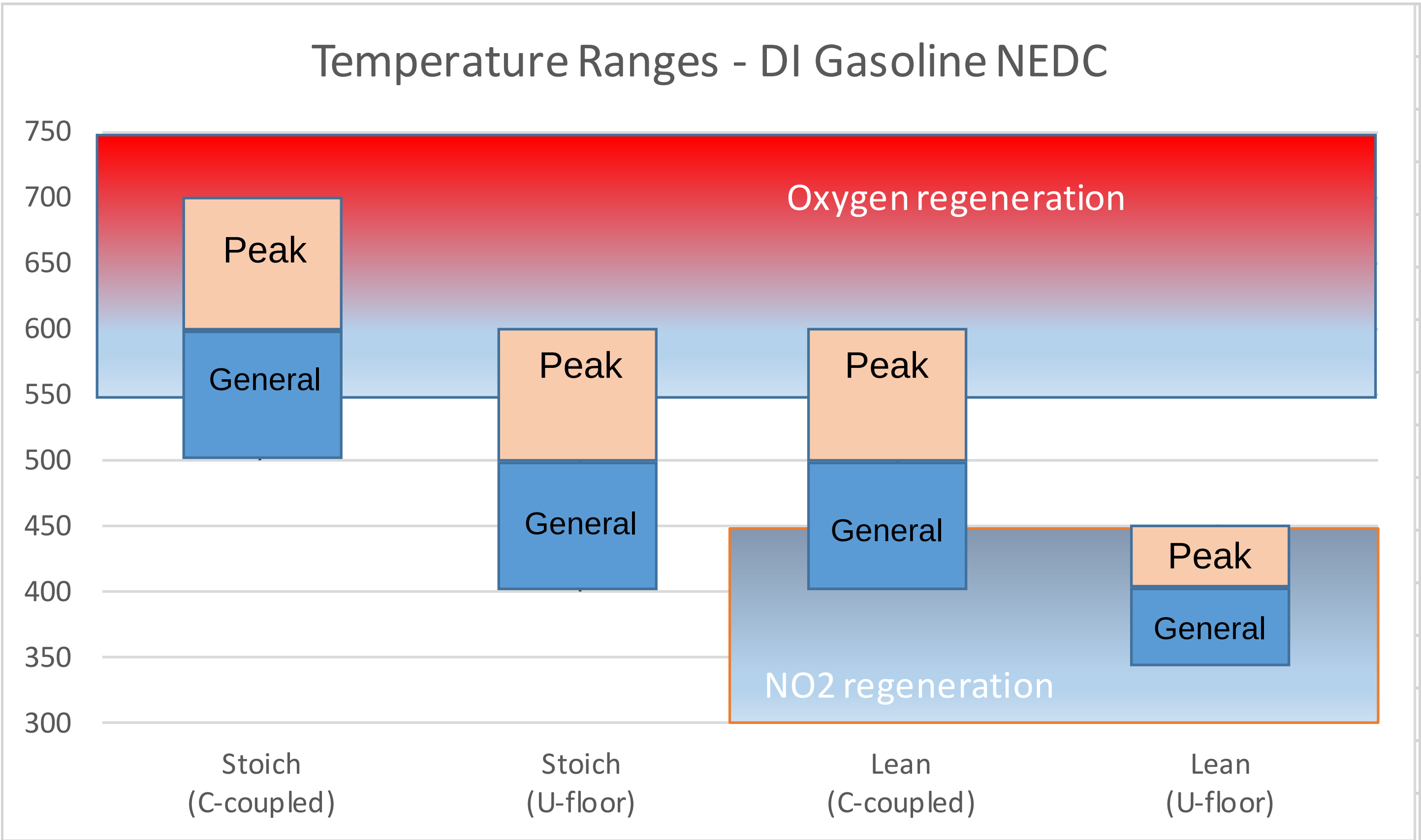


*includes particles from injector deposits or CCDs

Possible GPF applications (other AT components and specific layout options omitted)



Gasoline DI – Regeneration Opportunities Oxygen and NO_2



- High probability that gasoline vehicles won't need active regeneration strategies in normal mixed operation
  - Most vehicles will be able to use oxygen
  - There is a possibility of using NO_2 for lean DI if GPF is in a challenging (lower temp) position, but no obvious reason for putting the GPF there. Opportunities for using NO2 will be limited if the GPF is post LNT

High probability that 'active' regeneration will be unnecessary for gasoline DI vehicles

- Exhaust of lean DI has plentiful oxygen to burn soot, and even stoich DI has 0.7 to 1% O_2 present
- Close-coupled catalyst on stoich and lean DI will see temps high enough to 'passively' regenerate soot during normal operation – and these events will be frequent, if not continuous
- High speed / high temperature events are likely to see continuous regeneration
- Lean spikes could potentially be employed to create short exotherms to commence soot combustion
- No obvious reason for GPF in underfloor position on lean DI, but even if this was the case, configuring catalysts: TWC – GPF – LNT would enable some passive regeneration using NO_2
- Fuel shut-off may act as periodic regeneration event, rapid increase in AFR leading to combustion of trapped carbon and HCs

Unlike LD diesel vehicles, where active thermal regeneration by in-cylinder means or additional injector is essential, any 'regeneration events' on Gasoline DI will be likely part of normal operation

Events will occur frequently during normal driving and will be oxygen-based

No vigorous exotherm will be involved and there will be no excess fuelling

Minimal use of NO_2 regeneration expected

Passive Regeneration Events and Effects

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Regeneration Opportunity	Effects	Impacts	Potential Regulatory Implication
Fuel shut-off	• Short-term dramatic enleanment and increase in exhaust temperature leading to soot combustion • Combustion pressure lowered and oil may be released from ring pack • Manifold pressure is also lower and oil could be released from the crank-case breather system into the intake, this could pass through to the exhaust	• Reduction of soot on GPF, may continue following tip-in. • Consumed oil may lead to formation of semi-volatile particles, ash may be released	• Temporary reduction in GPF filtration efficiency • Creation of non-carbon solid PN from oil HC • <23nm metal oxides from ash
Lean spike	• Short-term increase in AFR leading to soot combustion	• Reduction of soot on GPF	• Temporary reduction in GPF filtration efficiency
Prolonged high speed cruise / high temperature operation	• Continuous regeneration of GPF. • Small exotherm across GPF. • Prolonged elevated exhaust temperatures similar to those seen from diesel active regeneration, but potentially longer duration	• Potential return of GPF to ‘empty’ state. • Release of HCs ahead of flame-front on GPF • Release of large amounts of low volatility HC deposited in exhaust system • Purge of stored sulphur compounds from catalytic surfaces	• Reduction in GPF filtration efficiency • Significant levels of volatiles in exhaust could challenge VPR efficiency • Stabilisation of GPF required for repeatability • Large numbers of sulphate nuclei could increase challenge on VPR efficiency

Summary of General Impacts of Soot Combustion of the GPF

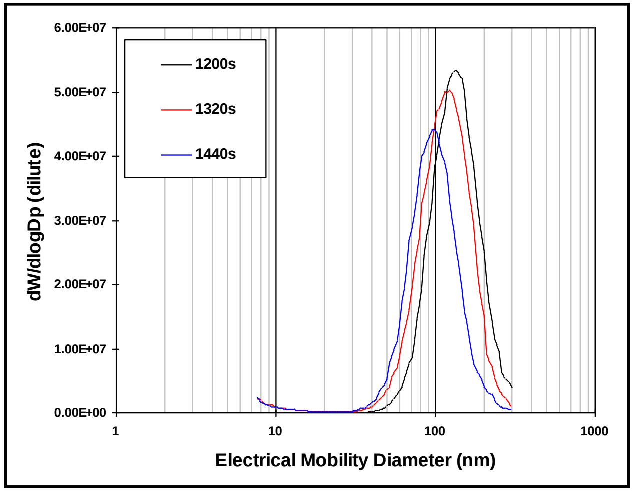
- It's anticipated that there will rarely be high levels of soot on a GPF, given the many opportunities for soot to be consumed during normal operation and lower engine-out levels than diesel
- PN limits are substantially closer to engine-out levels than in the diesel case, so more open GPF structures with lower efficiencies may be employed
- These frequent passive regeneration events, low soot emissions and loadings lead to predictable effects, though the magnitude of impacts are not well understood:

Phenomenon	Effects	Impacts	Concerns
Soot combustion on GPF	• Filtration efficiency of the GPF reduces • Flame front liberates volatiles stored on soot • Captured oil combusts and/or evaporates • Metals held within the soot are freed	• PN may escape at an enhanced rate after oxidation ceases • Exhaust HC may show minor increase temporarily • Oil may be released from the GPF • Ash may be created from oil combustion or released from storage on the GPF	• Impacts on repeatability for regulatory approval tests • Unpredictable elevations of HC • Increases in low-volatility HC particle formation • Releases of solid <23nm ash particles • Recombination of oil and ash during cooling may lead to formation of apparent solid PN

Areas worthy of study

- Evaluation of impacts on GPF filtration efficiency
  - Fuel shut-off, high speed cruise, lean spike
- Determination if GPF efficiency ever stabilises
  - Is it possible to load to a stable soot level?
  - How does the standard pre-con influence fill-state?
  - What is the best repeatability achievable for a sequence of tests on a GPF-equipped vehicle? (Is the only way to get repeatable data having an 'empty' GPF?)
- Worst case scenario investigations
  - Granny cycle operation – does soot combustion still occur even in this unfavourable mode? Might require lean spike to resolve?
  - Sustained high speed operation – impacts on release of low volatility materials
    - Does this happen on EUDC; Ex-H phase of WLTC?
    - Do we see large numbers of particles formed:
      - volatiles / non volatiles?
      - >23nm?
    - Do these particles challenge the VPR efficiency?

Part 2- DPFs



6.00E+07
5.00E+07
4.00E+07
3.00E+07
2.00E+07
1.00E+07
0.00E+00
dW/dlogDp (dilute)
1200s
1320s
1440s
1
10
100
1000
Electrical Mobility Diameter (nm)

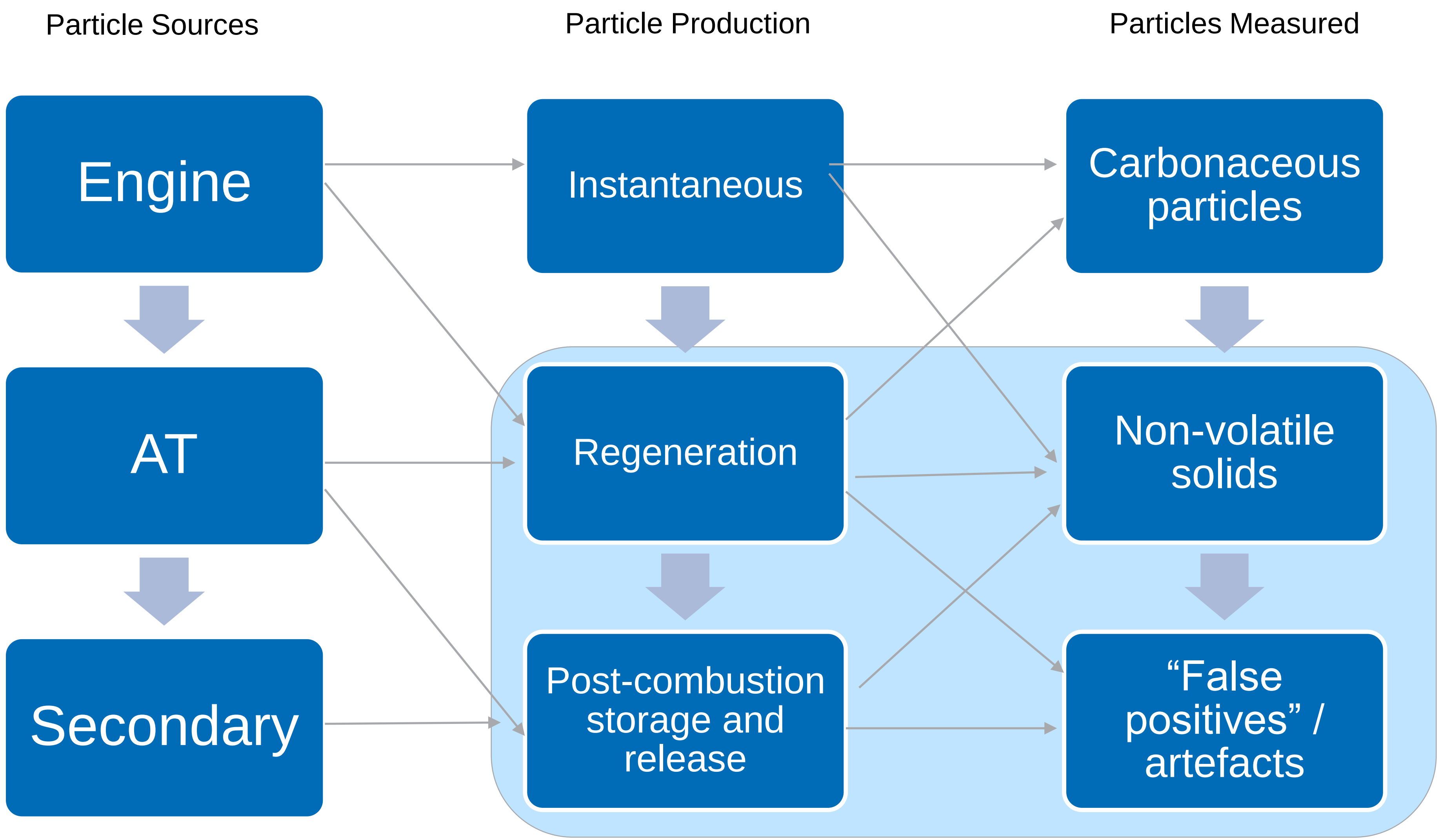
Contents – Part 2

- Technical Background
- Particle Production in Diesel Engines
- Influences of Hardware and Procedures
- ‘Passive’ regeneration with O_2 and NO_2
- Active Regenerations
- NOx emissions control
- Regeneration Implications
- Other factors important for PN methodology
- Impact of DPF-borne soot combustion on PN
- Areas worthy of study

Technical Background

- The contribution of PN emissions from active regenerations is not currently included within the R83
  - at the time of development evidence suggested that contributions of solid PN from regeneration events had a minor impact on overall emissions
- Subsequently, DPF sizes, filtration characteristics and material options have evolved, regulated emissions thresholds have been revised and more complex NOx and PN aftertreatment combinations are being employed
  - together these have resulted in changes to the strategies employed for regeneration
- These changes may require modifications to the regulatory PN procedure to adequately measure particle from regenerations. The implications of the regenerations on PN emissions during normal operation should also be considered

Particles from Diesel engines – sources and influences on regulatory procedures (1) – Particle Generation



Particles from Diesel engines – sources and influences on regulatory procedures (2): Influences of Hardware and Procedures

- Internal discussions at Ricardo identified the following areas for consideration regarding PN emissions during regeneration and possible impacts on existing regulatory procedures

Vehicle

- Vehicle application : Large displacement, aggressive downsizing
- Active regeneration approaches and strategies
- Passive regeneration opportunities: NO2 and O2
- Particles from SCR or LNT

Procedural

- Preconditioning
- Tunnel / Transfer system background
- DPF Loading / Stabilisation
- Frequency of regeneration / Ki
- DPF porosity / permeability
- Lubricant formulation
- Fuel additives (FBC)

LD Diesel: Limited DPF regeneration opportunities using Oxygen and NO_2 for late-stages of Euro 6

- For late Euro 6 the ability of DPFs to passively regenerate will be dependent on the supply of NO_2 available, and this will be related to the NOx aftertreatment employed and it's location relative to the DPF. There are 4 scenarios likely to be seen, though engine-only measures for NOx control are not expected to be sufficient for RDE

Impacts of NOx reduction technologies on passive regeneration relative to Euro 5

NOx control	Real-World Emissions	Drive Cycle Emissions (NEDC)
LNT	Reduction (NOx consumed upstream of DPF)	Reduction (NOx consumed upstream of DPF)
SCR	No change / increase (NO_2 post-DPF desirable for SCR reaction)	Increase (NO_2 post-DPF desirable for SCR reaction)
SCRF	Reduction (NO_2 preferentially reacts with ammonia)	Reduction (NO_2 preferentially reacts with ammonia)
No NOx aftertreatment	No change (EGR deactivated)	Reduction

- SCR-only equipped applications will see appreciable opportunities for passive regeneration
- Despite close-coupled DPFs, limited opportunities foreseen for oxygen regeneration on LDD due to insufficient exhaust temperatures – except, possibly, in real-world highway use
  - Safe active regeneration strategies will be required for all LDD

Active DPF Regenerations will dominate

- From Euro 4 to 6 engine-out NOx and soot levels have changed and this has impacted the approach used to select DPFs and develop robust regeneration strategies

Engine out soot levels	DPF substrate material	DPF substrate location, size / characteristics	Active regeneration frequency	Active regeneration approach
Most Euro 4 vehicles achieved the PM limits (25mg/km) without applying a DPF. At Euro 5, lowered PM and PN limits forced DPF use, but exploiting the NOx/PM trade-off for NO_X reductions promoted higher engine-out PM (generally capped at ~50mg/km for OBD compliance). Euro 6.2 OBD will be as low as ~12mg/km suggesting a possible future reversal of this trend	Different ceramic DPF materials have different maximum soot loading capacities. Initial DPF applications were conservative, with oversized SiC DPFs. Cost-down and greater experience now sees the use of alternative materials (Aluminium Titanate) and Cordierite with lower soot loading capacities.	Almost all DPFs are now placed in a close-coupled position, are downsized (smaller capacity) and may have higher porosity to limit engine backpressure impacts on fuel economy, while enabling specialised coatings - and still safely meeting PN limits	Change of substrate material maximum soot loading (if not SiC), smaller DPF and highish engine-out soot means more frequent DPF regenerations are required. EO soot levels are calibrated according to measures taken to control NOx (engine only, LNT, SCR). In extreme cases DPF regen can be at ~100km intervals, but in large majority of cases, intervals are assumed to be shorter than at Euro 4	In-cylinder late post injection favoured, with good control of temperature (600°C) via feedback. Event can be of long duration (1 to 1.5 NEDC cycles). Heat-up profile smoothed to avoid excessive local exotherms, so 'milder' than earlier approaches. In-exhaust injection reduces fuel dilution / oil consumption

NOx emissions control approaches

- LNT, SCR and SCRF will be employed widely for NOx control at Euro 6
- LNT will be placed upstream of the DPF and will require periodic regeneration for removal of stored sulphur components
  - Potential for production of particles exists
- SCR will almost always be placed downstream of the DPF
  - Some SCR systems have been shown to develop deposits and sulphur compounds may also be stored. DPF regeneration will assist in cleaning these, but particles may be generated in the process
- SCRF will placed downstream of the DOC
  - Some SCR systems have been shown to develop deposits and sulphur compounds may also be stored. DPF regeneration will assist in cleaning these, but particles may be generated in the process
- For some high capacity applications combinations of SCR and passive NOx adsorber technologies might be employed

Regeneration Implications

- Changes in the approaches, DPFs and types of regenerations used for Euro 6 may have an impact on the particle number measurement procedure

Factor	Background	Impacts	Potential Regulatory Implication
In-cylinder late post injection active regeneration	• Common method for DPF regeneration. • Combined with throttling to provide exotherm and raise exhaust temperatures to ~600°C • Oil dilution is an issue and oil may enter the exhaust during the process	• Soot and HC combusts • Some HC may escape • Ash contained within soot may escape, ash within DPF substrate may escape • Thermal release of low volatility materials	• Large numbers of <23nm volatile particles • Potential increase in nuclei for condensation of heavy HC (ash / sulphates) • Heavy HCs might defeat VPR
In-exhaust active regeneration	• Less common method for DPF regeneration, uses additional fuel injector • Similar effects to in-cylinder approach, but without oil dilution	• Soot and HC combusts • Some HC may escape • Ash contained within soot may escape, ash within DPF substrate may escape • Thermal release of low volatility materials	• Large numbers of <23nm volatile particles • Potential increase in nuclei for condensation of heavy HC (ash / sulphates) • Heavy HCs might defeat VPR
Fuel borne catalyst	• FBCs not widely used, but associate with soot in combustion • Metallic additives dot the surface of the soot and catalyse soot combustion at lower temperatures (c. 450°C with oxygen)	• Higher porosity / lower backpressure DPFs may have reduced retention for metallic particles during and following active regeneration	• Increase in <23nm solid PN • Potential increase in nuclei for condensation of heavy HC
LNT regeneration	• Deactivation of LNT by stored sulphates requires thermal regeneration • Regeneration either as short event integrated within each DPF regen, or every few regeneration cycles • Possibly a discrete event	• Exhaust temperature elevated to 620 – 650°C • SO2 release from LNT • Highest exhaust temperature may lead to thermal release of low volatility materials elsewhere in exhaust	• (In addition to std regen) • Emissions of <23nm volatile particles • Potential increase in nuclei for condensation of heavy HC • Heavy HCs might defeat VPR

Other factors important for PN methodology

Factor	Background	Impacts	Potential Regulatory Implication
Increased frequency of DPF regeneration compared with vehicles considered in earlier PMP studies	• Engine-out soot, DPF, loading , efficiency may have changed • Changes may require more frequent active regenerations	• PN contributions from regen to overall emissions may be greater than previously measured	• Ki factor approach may be required • Potential increases in solid, volatile and <23nm particles
SCR-derived deposits	• SCR using aqueous urea can generate a variety of deposits with different volatilities • Some are easily decomposed at normal operating temperatures, others are more stable and require higher temperatures to remove	• Potential sites for deposition of semi-volatile materials post-DPF • Deposits volatilised during active regenerations may generate particles • Materials released may be cations	• Increased particles (uncertain of particle size) • Combination with sulphates to form solid PN
Preconditioning the vehicle and stabilising the DPF	• Preconditioning needs to consider both DPF and SCR • Stable DPF fill necessary for repeatable PN measurement	• Necessary DPF-fill for stable PN measurements likely to be dependent on DPF formulation • Change from prior 300km assumption	• Change to generic description needed in regulation?
Background contributions	• More frequent regenerations in test vehicles • More porous DPFs	• May lead to higher PN backgrounds in dilution systems with both semi-volatile and low levels of soot contributing	• Prior background contribution assumptions may be underestimates • Factor could be different for higher temp regenerations (e.g. LNT)
System contributions (transfer to CVS etc)	• More frequent regenerations in test vehicles • More porous DPFs	• Transfer system may become more contaminated than with older, higher efficiency DPFs with less frequent regenerations	• Importance of contribution to certification tests could be increasing

Summary of General Impacts of Soot Combustion on the DPF

- The use of a wide variety of DPF sizes, porosities and compositions will lead to a wide range of soot loadings and differences in filtration efficiencies. Compared to older engines, this will widen the range of both ‘cleaned efficiencies’ - immediately following regeneration, and the total range of filtration efficiencies seen across all DPFs on all engines
- The main impacts of soot regeneration on DPFs are given below

Phenomenon	Effects	Impacts	Concerns
Soot combustion on DPF	• Filtration efficiency of the DPF reduces • Flame front liberates volatiles stored on soot • Captured oil combusts and/or evaporates • Metals held within the soot are freed	• PN may escape at an enhanced rate after oxidation ceases • Exhaust HC may show minor increase temporarily • Oil may be released from the DPF • Ash may be created from oil combustion or released from storage on the DPF	• Impacts on repeatability for regulatory approval tests • Unpredictable elevations of HC • Increases in low-volatility HC particle formation • Releases of solid <23nm ash particles • Recombination of oil and ash during cooling may lead to formation of apparent solid PN

Areas worthy of study

- Evaluation of magnitude of PN increase with active regeneration
  - Increase if LNT regen included, or separate
  - Impact of FBC (include <23nm)
- Determination of ‘typical’ regeneration frequency
- Determination of DPF efficiency stabilisation
  - How long to load to a stable soot level?
  - How does the standard pre-con influence fill-state? What else should/could be done?
- SCR deposits – are these an issue, and if so, how big?
- Consideration of background and sampling system PN contributions