Direct Injection Gasoline Engine Particulate Emissions

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Overview

- Introduction
  - Direct injection gasoline engines as enablers to CO_2 emissions reduction
  - Mixture preparation
  - Operating modes (stratified & homogeneous charge)

- PM emissions data – early vehicles on legal drive cycles

- PM formation mechanisms in direct injection gasoline engines
  - Imperfect mixture preparation
  - Wall wetting and pool fires
  - Stratified charge

- PM control
  - Combustion system design, calibration and fuel composition

- Conclusions

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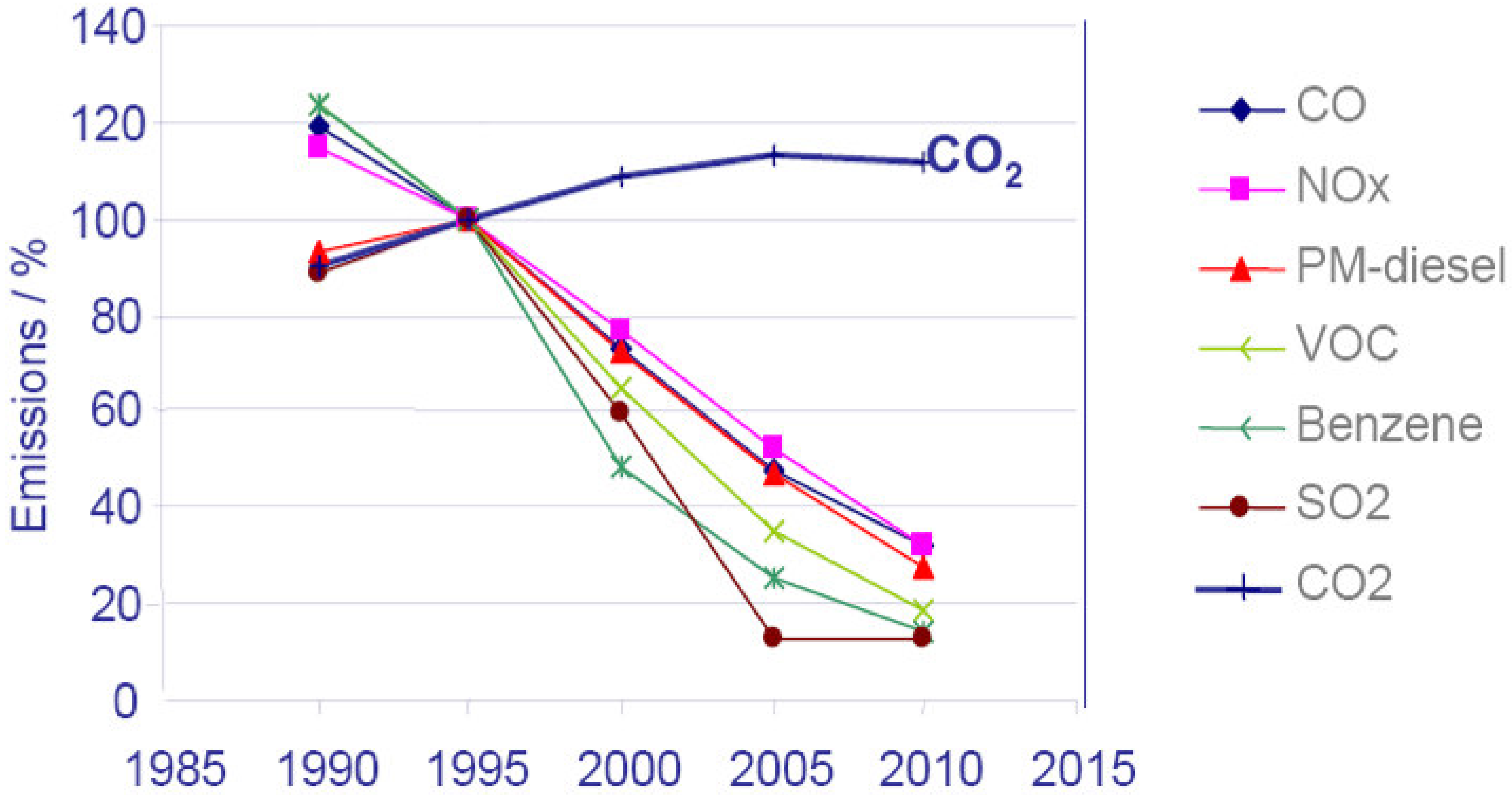
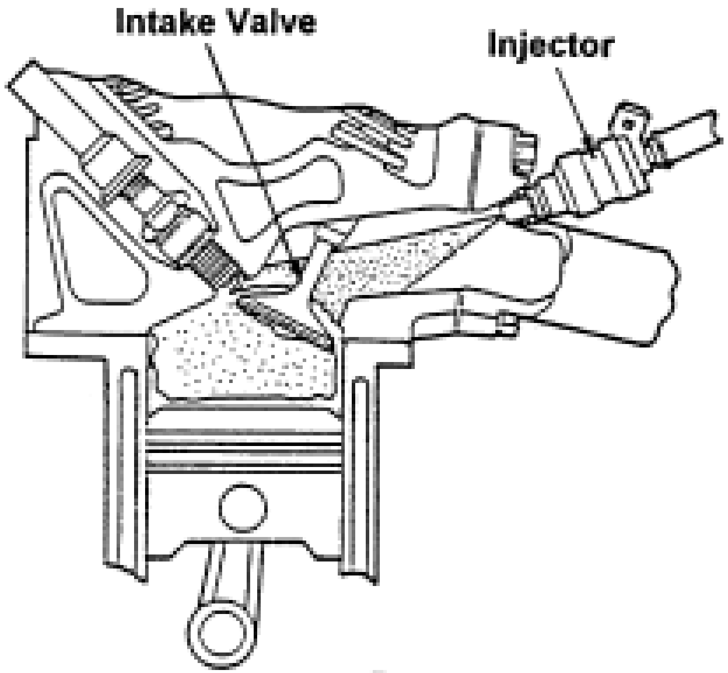
Development of Road Traffic Emissions

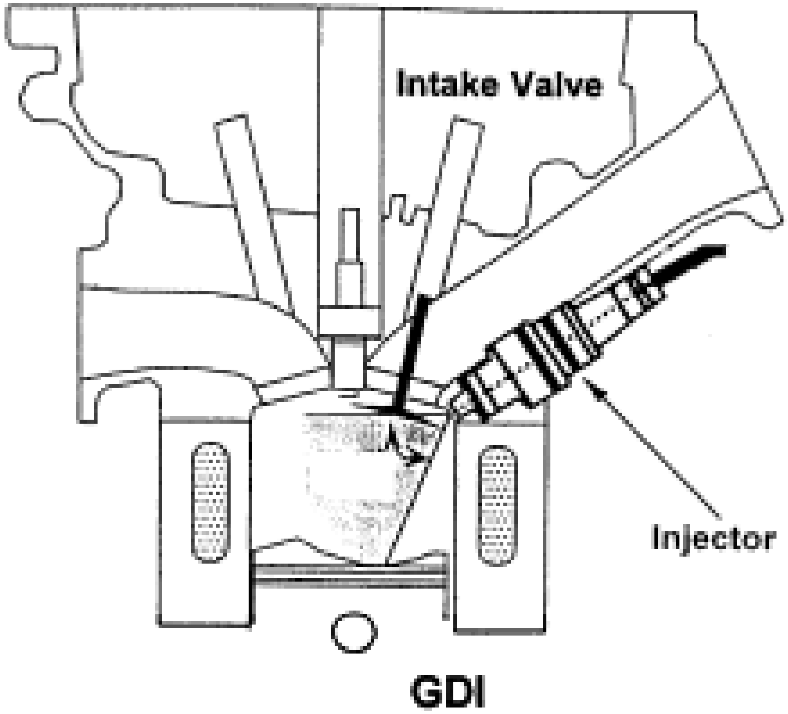


Source: EC Auto-Oil-2 Program

Huge progress demonstrated in the reduction of criteria pollutants. CO2 remains as the challenge.
Gasoline engine efficiency needs to be improved to help meet future CO2 legislation.

Gasoline Direct Injection





Figures from Zhao, F *et al.*
Progress in Energy and Combustion Science 25 (1999) 437–562

Direct fuel injection is one of many technologies being used to improve gasoline engine efficiency, hence reduce CO2 emissions.

DI gasoline engine efficiency

- Higher specific power (charge cooling & intake port fuel vapour displacement), hence downsizing with associated reduction in part-load throttling losses.

- Compression ratio increase (due to charge cooling effect) with associated increase in cycle efficiency.

- Lean stratified operation at part-load with associated reduction in throttling losses, but requires after-treatment for NOx with fuel penalty for purge events

- Synergies with forced induction – charge cooling / compression ratio increase improves low end torque. Forced induction enables further downsizing.

- Taken together, fuel economy improvement over PFI may be as large as 15% on the FTP-75 cycle. Alkidas, A *et al.* SAE 2003-01-3101.

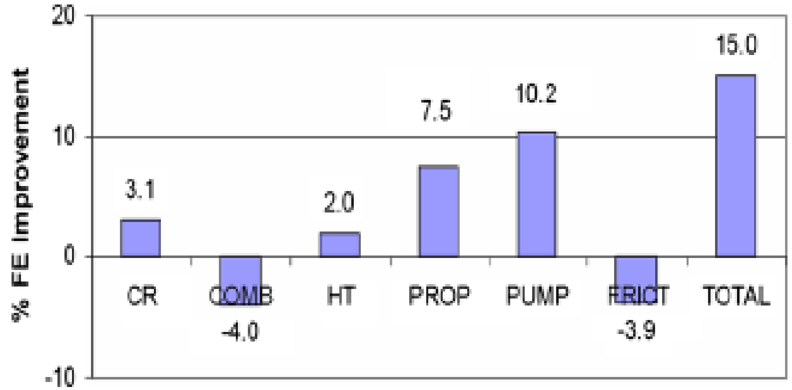
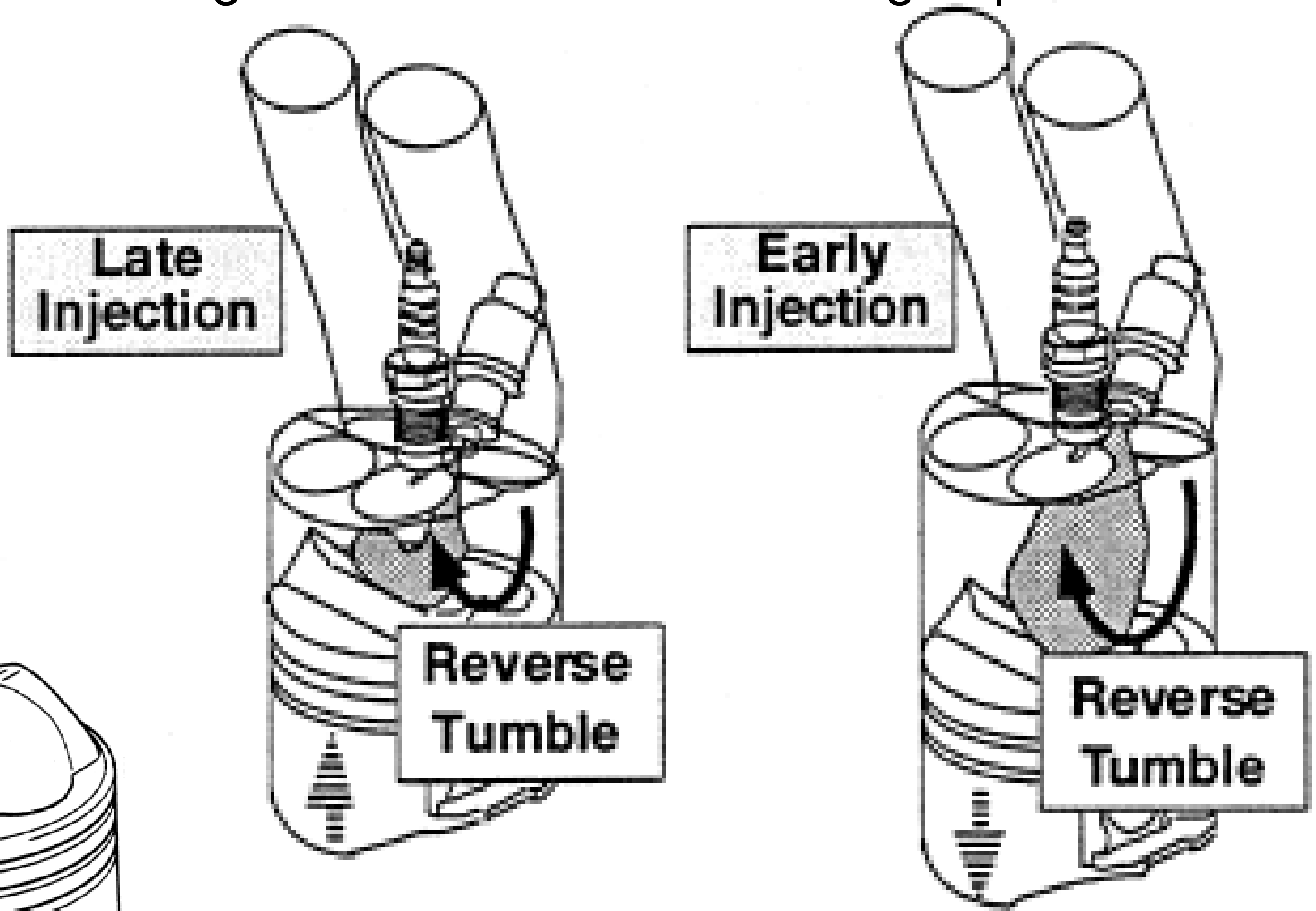
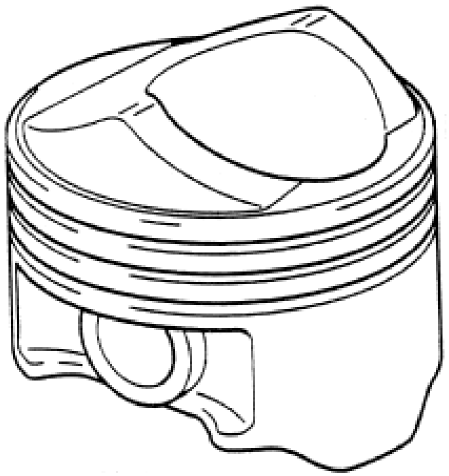


Figure from Alkidas, A *et al.* SAE 2003-01-3101

Mixture preparation in early direct injection gasoline engines – homogeneous and stratified charge operation





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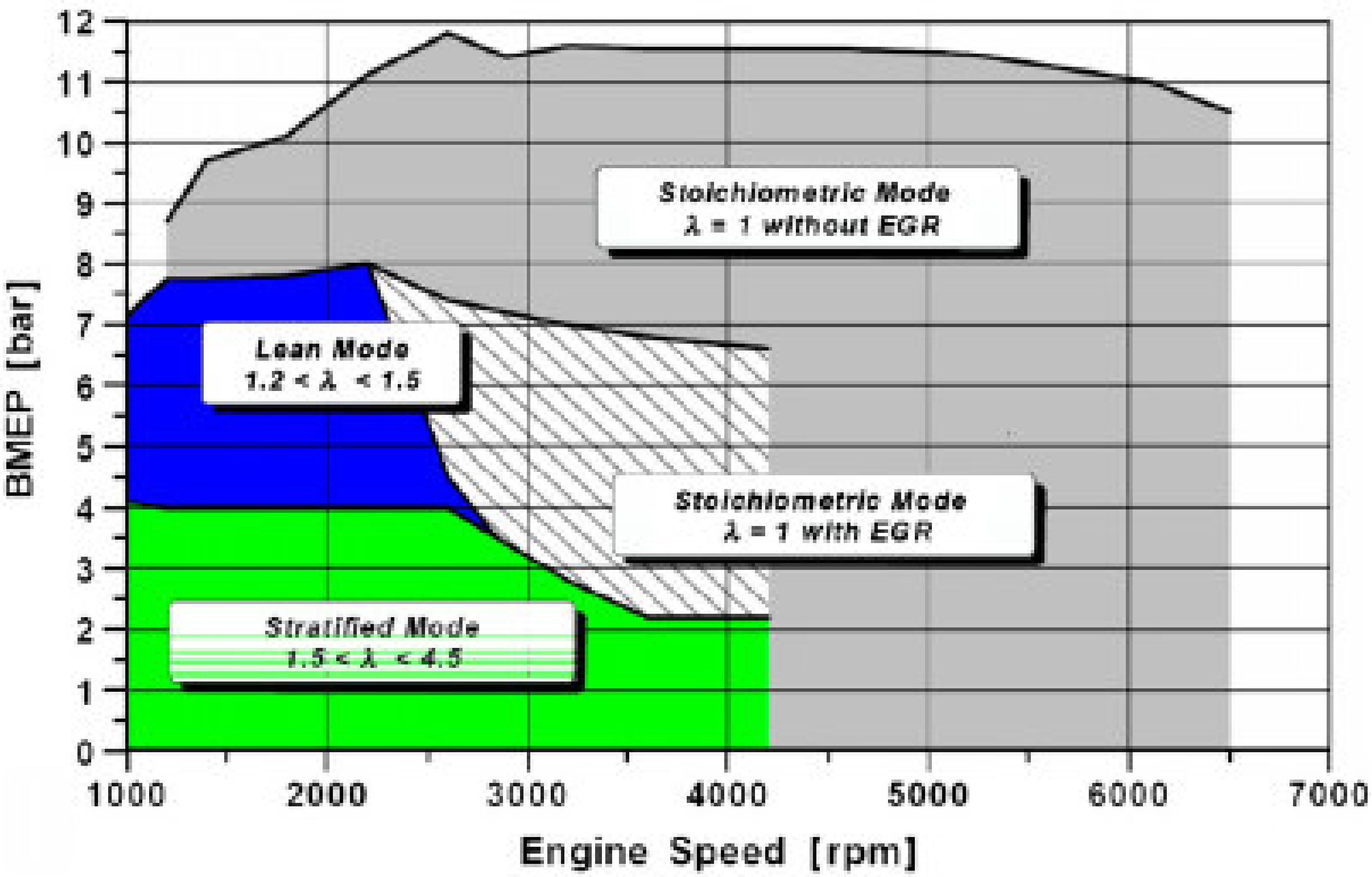
DI Gasoline Engine Operating Modes



- Maximum CO2 benefit obtained when lean / stratified operation is used at part load

Figure from Salber, W *et al.*
SAE 2002-01-0706

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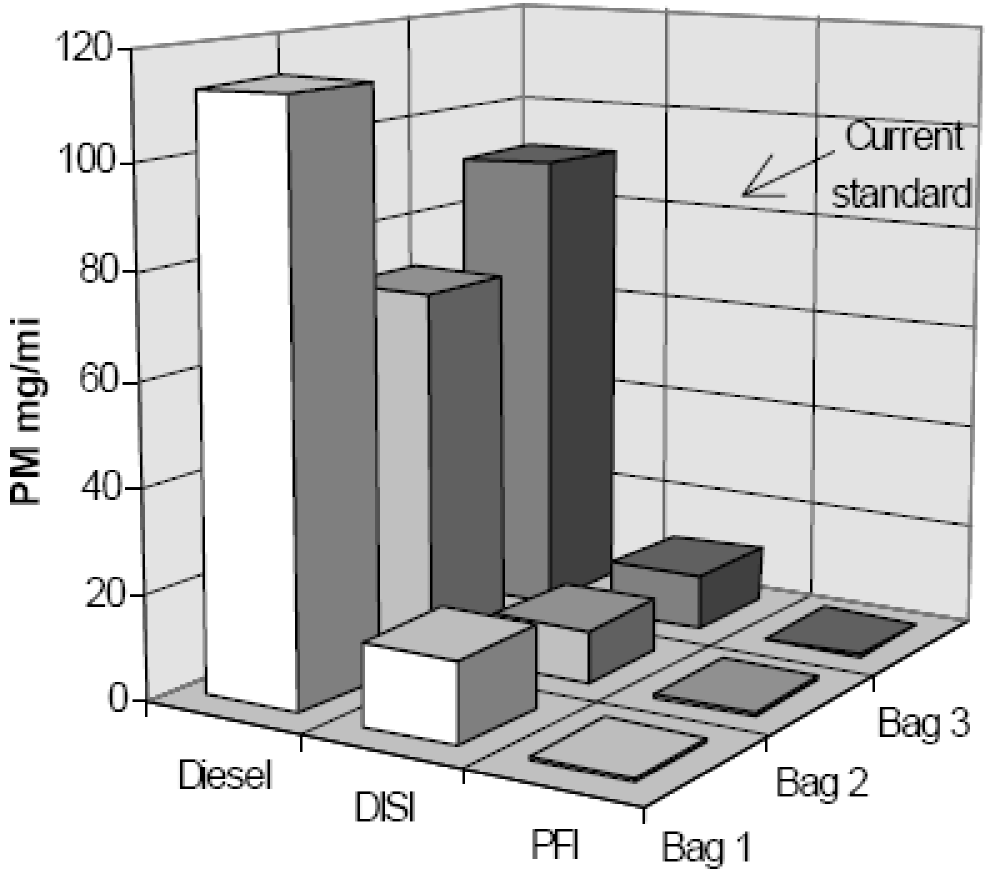
Early DI gasoline technology compared to port-fuel injection and diesel - PM mass FTP-75 drive cycle



Maricq, M M *et al.* SAE 1999-01-1530

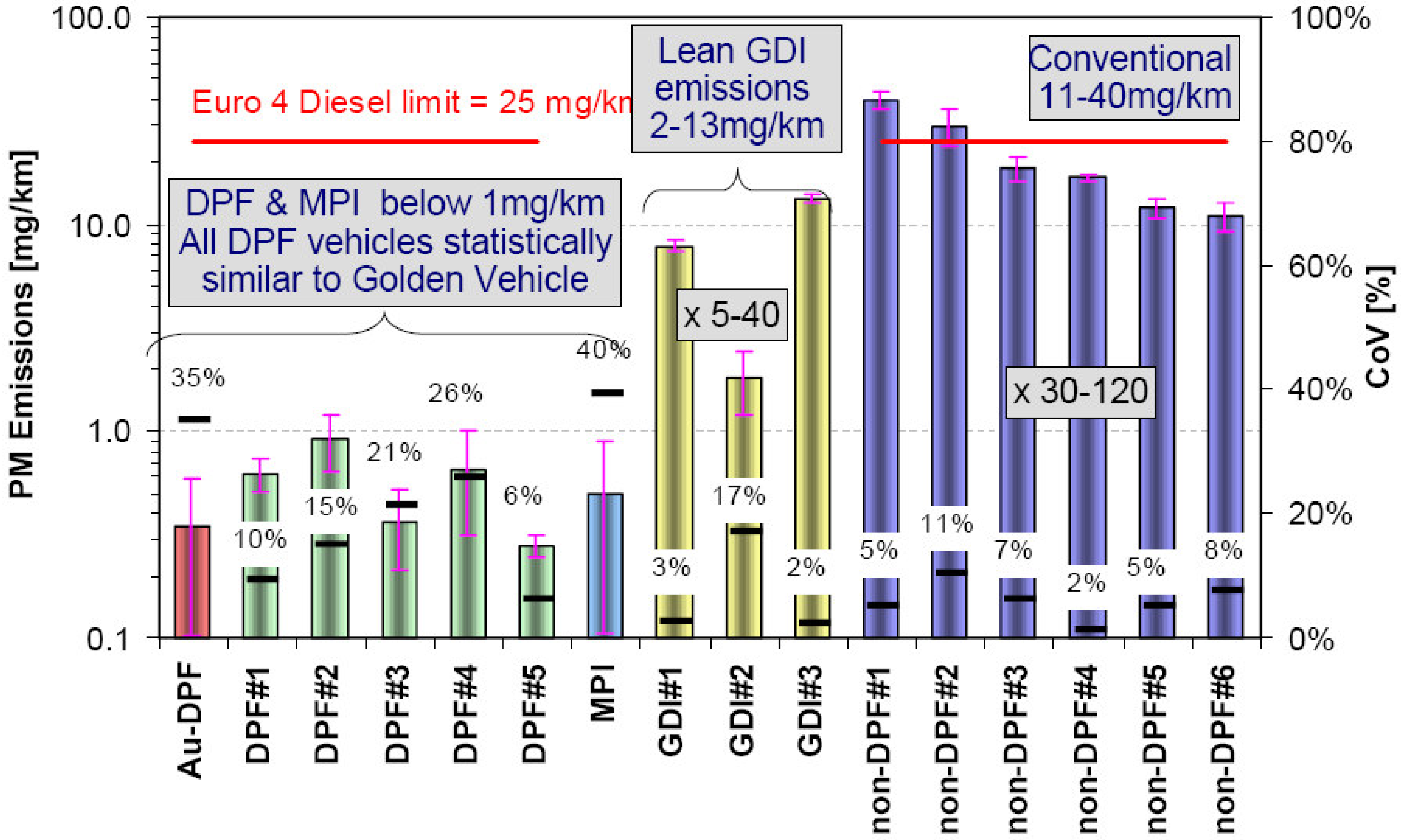
Diesel: European 1995 IDI engine.

DISI: Wall guided 1999 Production vehicle (stratified & homog. modes)

PFI: US 1999 Port Fuel Injection engine.

Early DISI vehicle PM emission rates lie between diesel and PFI on the FTP-75 cycle

PM mass comparison – various vehicles on the new European driving cycle



Department for Transport

Figure from Chris Parkin, DfT

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PM formation mechanisms in direct injection gasoline engines - **Imperfect mixture preparation**

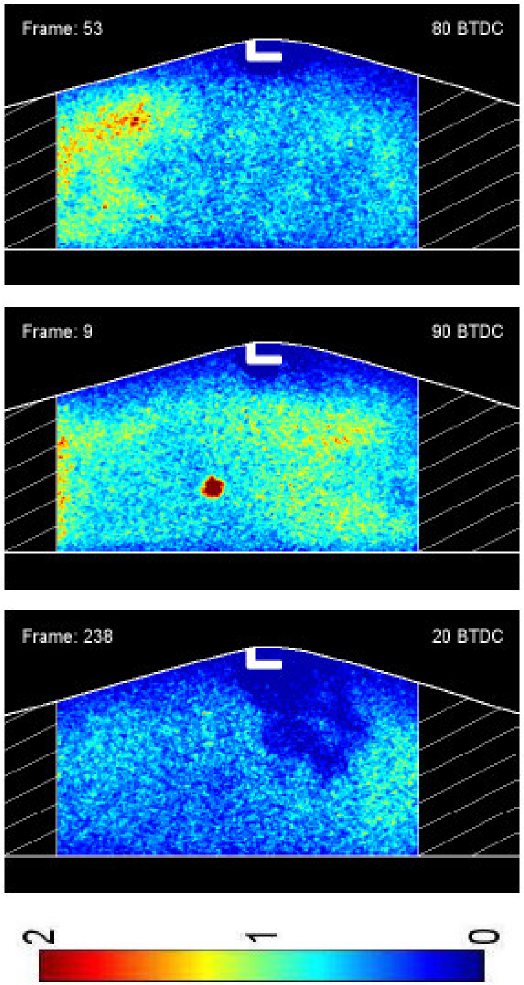

Figure from Williams et al. SAE 2008-01-1073

- Time available for mixture preparation reduced *cf* PFI - typically a few milli-seconds between end of injection and spark.

- Non-uniformity in spatial distribution of AFR, even in a nominally homogeneous charge.

- Incomplete evaporation of fuel leading to the existence of liquid droplets at ignition

- Hence, volatile organic and carbonaceous PM formed by locally rich combustion and from pyrolysis or partial burning of fuel droplets

PM formation mechanisms in direct injection gasoline engines - **Wall wetting & pool fires**

- In cylinder injection at ~100 bar fuel pressure often results in fuel impingement on combustion chamber surfaces, e.g. on the piston crown.
- Fuel may not completely evaporate before spark, particularly if heat transfer is hindered by Leidenfrost effect.
- Pool fires burn diffusively through expansion and into the exhaust strokes.

Figure from Stevens & Steeper SAE 2001-01-1203

- Significance dependent on combustion system geometry and calibration. Noting particularly strong response to injection timing, but trading off impingement against time for mixture preparation.

PM formation mechanisms in direct injection gasoline engines - **stratified charge mode**

- Some DI engines can operate in a stratified charge mode at part load. Charge will be lean overall, but stratified and flammable around the spark plug at ignition.

- Very late (compression stroke) fuel injection means that the time available for droplet evaporation is small – droplets of fuel and surviving ligaments from the nozzle exist at spark.

- Locally rich zones in the stratified region responsible for soot production, probably not helped by little post-flame oxidation, high incidence of partial burns and misfires.

- Several authors report an increase in PM mass rates of 10 – 100 times going from homogeneous to stratified operation

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DI gasoline engine PM control

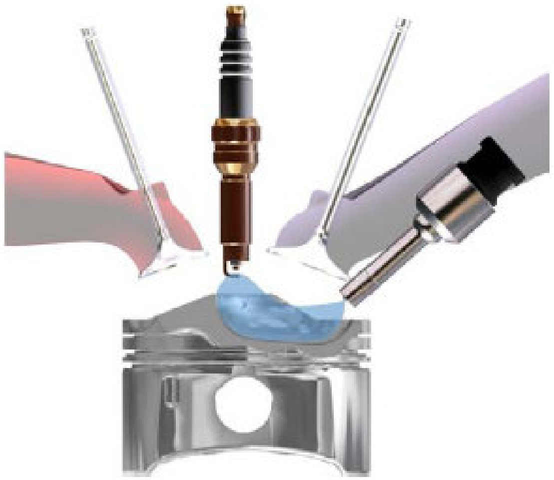
- Combustion system
  - Geometry and mixture preparation – wall guided systems unlikely to be tenable going forwards
  - Fuel injection equipment, particularly injectors– spray pattern, droplet size Injector design. Early data from ‘spray guided’ combustion systems shows lower PM & PN emissions

- Calibration:
  - Fuel pressure, injection timing and ignition timing responses demonstrated. Ignition retard effective for improving combustion efficiency but with CO2 penalty.
  - Split injection strategies likely to be employed, but limited by FIE cost.

- Fuel composition
  - PM & PN strongly dependent on fuel composition – more so than for most of the above
  - Generally *alkanes < alkenes < aromatics < poly-aromatics* holds for DI gasoline. Increased response to calibratables noted for aromatics
  - Oxygenates (e.g. Ethanol, Butanol) good at suppressing PM, but also suppressing response to calibratable control factors
  - Further scope for PM reduction by gasoline formulation, including additives?

Developments in mixture preparation concepts

Wall Guided
Side Mounted Injector



Spray Guided
Center Mounted Injector

SGDI now emerging as the dominant technology – good news for PM & PN.

Reduced contact between fuel and combustion chamber surfaces.

Higher fuel pressure therefore better spray atomisation and ultimately improved mixture preparation.

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- Reduction of CO_2 emissions is priority number one for research and development engineers in the automotive industry. DI gasoline is just one of several technologies emerging to reduce CO_2 from road transport

- PM & PN from early production systems was not negligible – particularly for stratified operation. Most data suggest PM between PFI gasoline and non-DPF diesel

- PM mechanisms are as follows
  - Imperfect mixture preparation
  - Wall wetting & pool fires
  - Stratified charge – locally fuel rich combustion

- PM control
  - Spray guided combustion systems represent a significant step forwards for quality of mixture preparation & avoidance of wall wetting
  - PM response to calibration becoming clearer – injection timing, AFR, fuel pressure & ignition timing demonstrated as key control factors for optimisation
  - Fuel composition has a role to play – aromatics increase soot production whilst oxygenates help suppress soot.

Thank you for your attention