European Commission

Enterprise and Industry
Directorate-General

Particle number emission limits for Euro 6 positive ignition vehicles (PI)

15. ETH Conference on Combustion Generated Nano-particles
Zurich, 27 – 29 June 2011

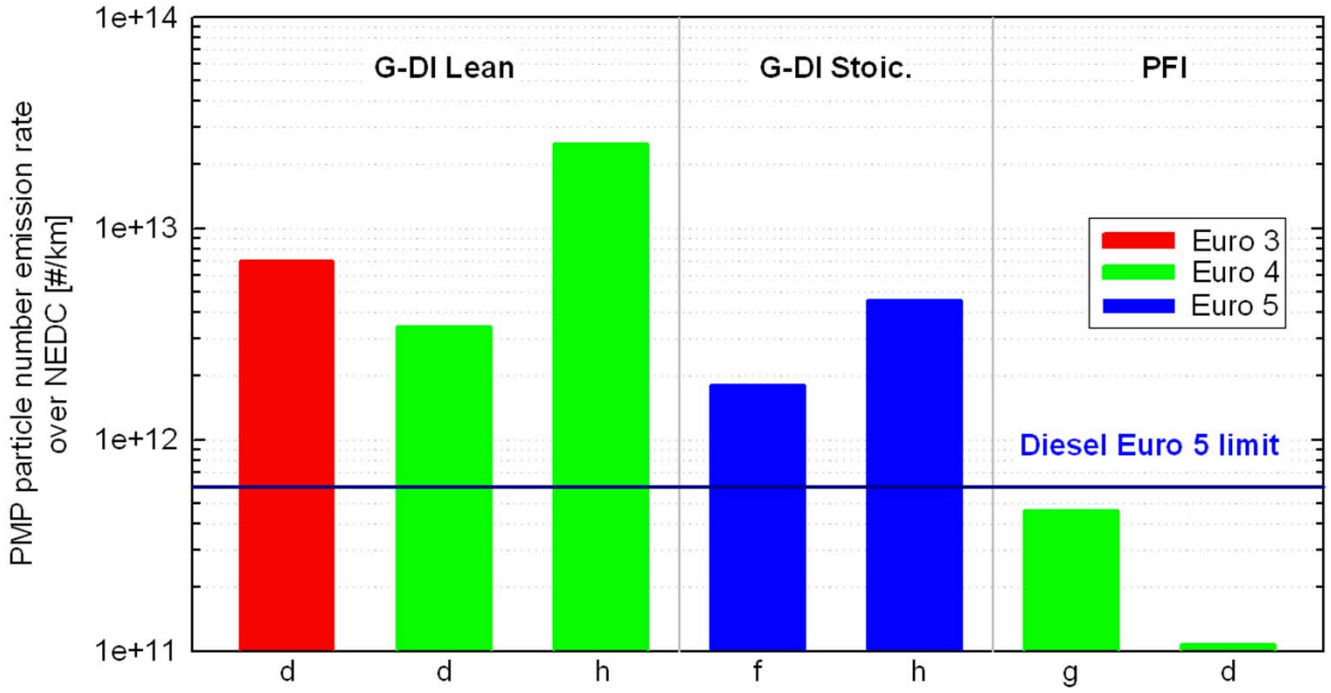
PN emission limits for PIV

- Legal/political background
- PN emissions of current technology PI
- Effects on air quality
- First conclusions
- PN abatement: technology & costs
- PN abatement: health benefits
- Conclusions and “to-dos”

Legal/political background: Euro 5/6

- Particle mass (PM) emission limit of 4,5 mg/km applicable to compression and positive ignition direct injection vehicles (PIDI)
- Particle number (PN): number of solid, non-volatile particles larger than a certain minimum size (e.g. 23 nm)
- PN emission limit of **6 x 10^{11}/km for compression ignition vehicles (CI**) as from 1 September 2011(Euro 5b)
- PN emission limit to be defined for PI by "Comitology" (COM Reg, vote in regulatory Committee of Member State experts => "fast track") **before 1 September 2014**
- Technology neutral assumption: identical PN emission limits for PI and CI
- But: cost/benefit pattern different

PN emissions of current technology PI

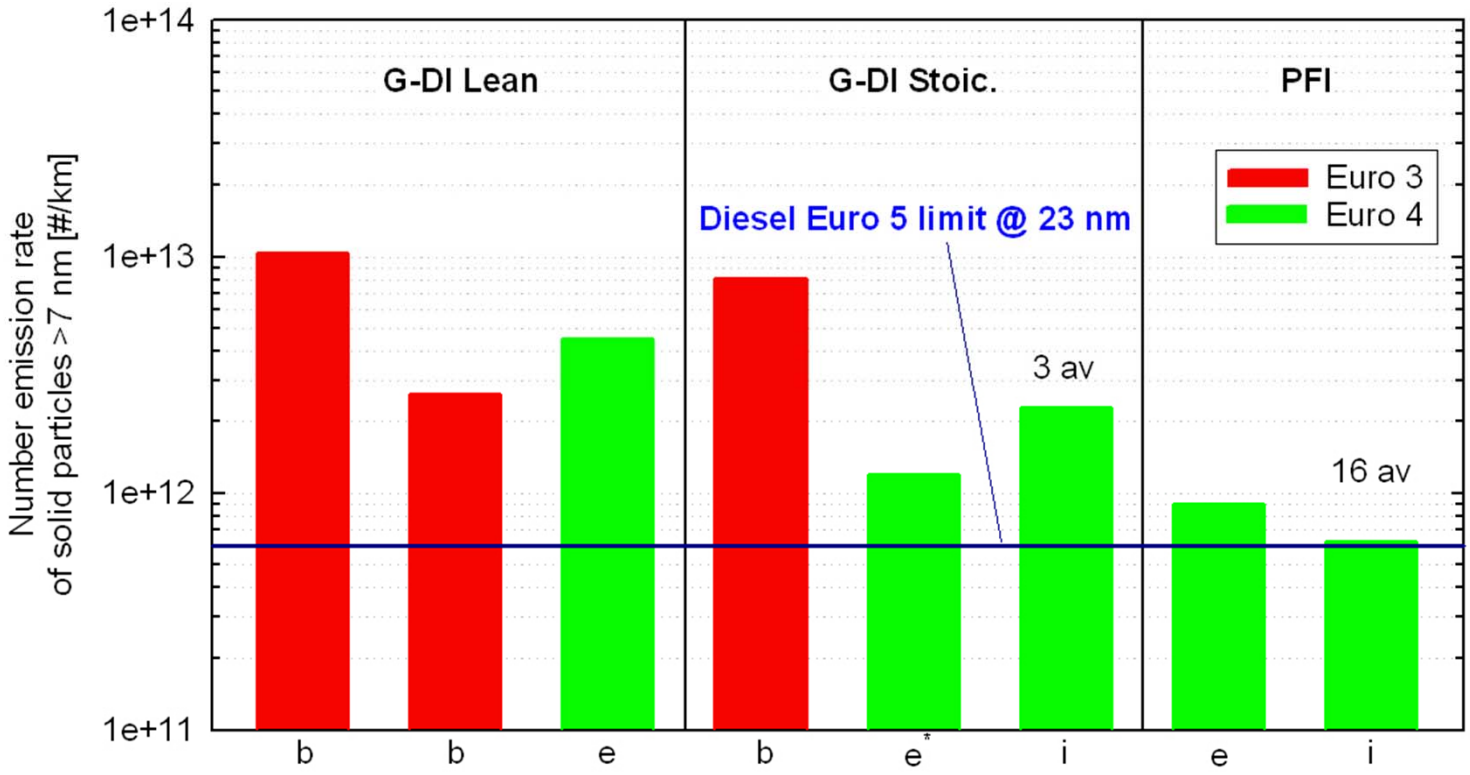


Reported particulate number emissions of gasoline powered vehicles of different fuel injection strategies and emission standards over the NEDC following the legislated procedure for diesel vehicles. d: Andersson et al. 2007, f: Mikulic et al. 2010, g: Bosteels et al. 2006 [[i]], h: Braisher et al. 2010 [[ii]].

[i] Bosteels D., Mas C. J., Karlsson H. and de Serves (2006). 'Regulated' and 'Non Regulated' Emissions from Modern European Passenger Cards. SAE Technical Paper 2006-01-1516.

[ii] Braisher M., Stone R. and Price P. (2010). Particle Number Emissions from a Range of European Vehicles. SAE Technical Paper 2010-01-0786.

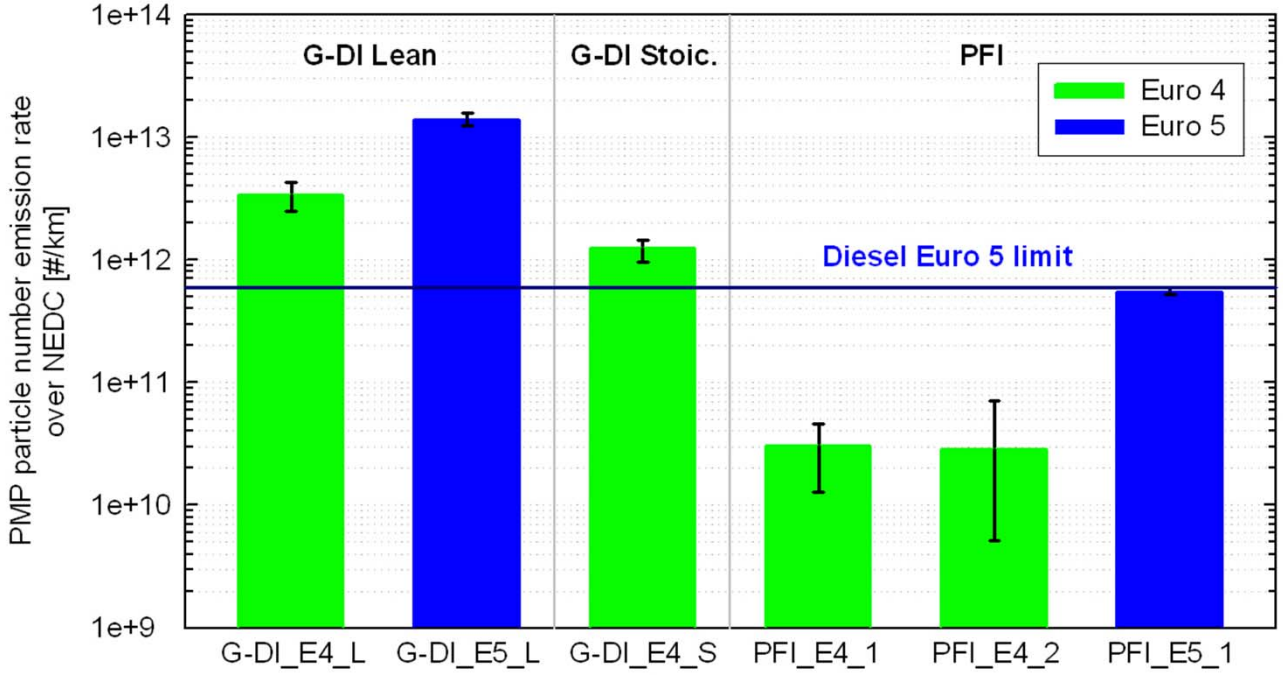
PN emissions of current technology PI



Reported number emission rates of solid particles larger than 7 nm over NEDC for gasoline vehicles of different fuel injection systems and emission standards. b: Mohr et al. 2003, e: Mohr et al. 2006, i: Schreiber et al (2007) [[i]], figures correspond to the average value of 3 stoichiometric G-DI and 16 PFI gasolines, e*: figure corresponds to the average of 3 tests of a lean G-DI which operated in stoichiometric mode over the particular repetitions.

PN emissions of current technology PI

Study by the JRC (Athanasios Mamakos, Giorgio Martini), January 2011:



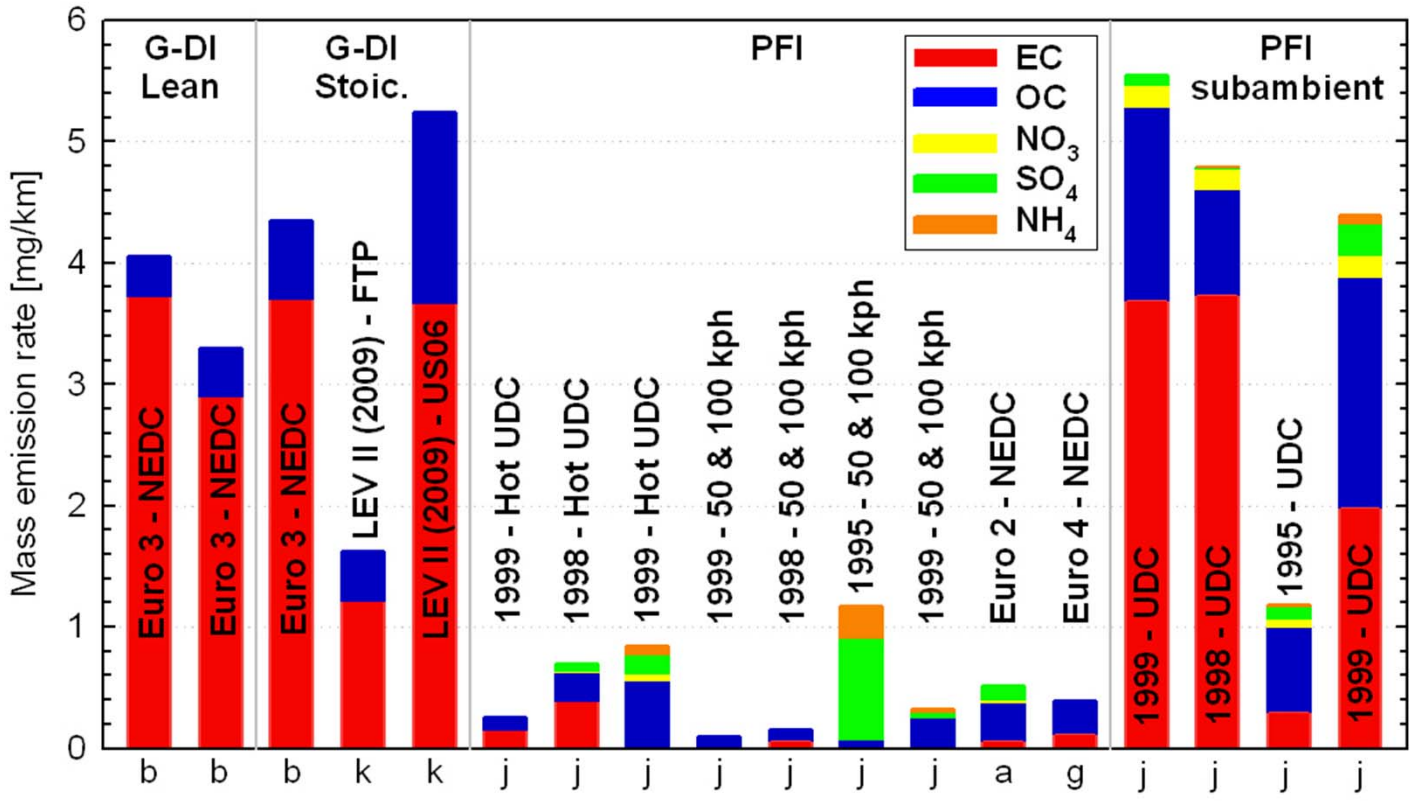
Confirming literature results (e.g. SAE, Env. S&T) for PN emissions:

- For PI port fuel injection (PIPF) on NEDC close to Euro 5/6 CI limit value

- For PIDI systematically above Euro 5/6 CI limit value

All PI meet Euro 5/6 PM emission limit value!

PN emissions of current technology PI



Reported chemical composition of PM emitted from gasoline powered vehicles. The vehicle technology (emission standard or model year) and test cycle are given explicitly on each bar. A: Andersson et al. 2001, b: Mohr et al. 2003,g: Bosteels et al. 2006, j: Schauer et al. 2008, k: Khalek et al. 2010.

PN emissions of current technology PI

Study by the JRC (Athanasios Mamakos, Giorgio Martini), January 2011:

➢PIPF

– All PIPF vehicles can easily comply with a PM limit of 4.5 mg/km but also the PMP PN limit of 6×10^{11} #/km

– The particle emissions increase significantly under unregulated test conditions, in particular at start up, under sub-ambient test temperatures and more aggressive test cycles (US06)

– The test temperature and test cycle effects are more evident in particle number emissions

➢PIDI

– Late technology PIDI vehicles were found to comply with the PM limit of 4.5 mg/km

– None of the PIDI vehicles tested at JRC complied with the 6×10^{11} #/km limit, and there is no published data in the literature of PIDI vehicles complying with this limit without the use of particulate filter

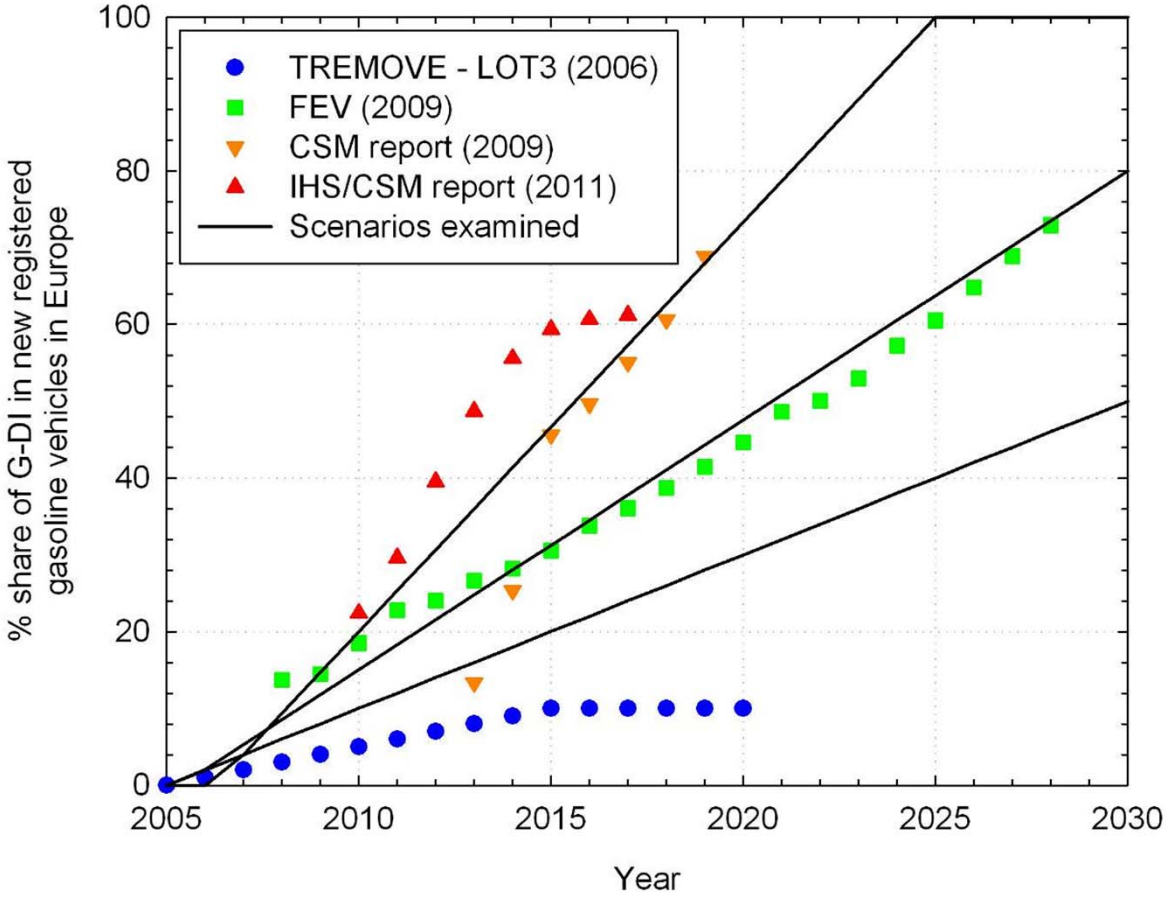
– Euro 3 PIDIs (4 vehicles): $1{,}7 \times 10^{13}$ #/km; Euro 4/5 (7 vehicles): $7{,}6 \times 10^{12}$ #/km

– No strong “off-cycle” effects

Effects on air quality

Effect of PIDI on air quality if no PN emission limit is introduced?

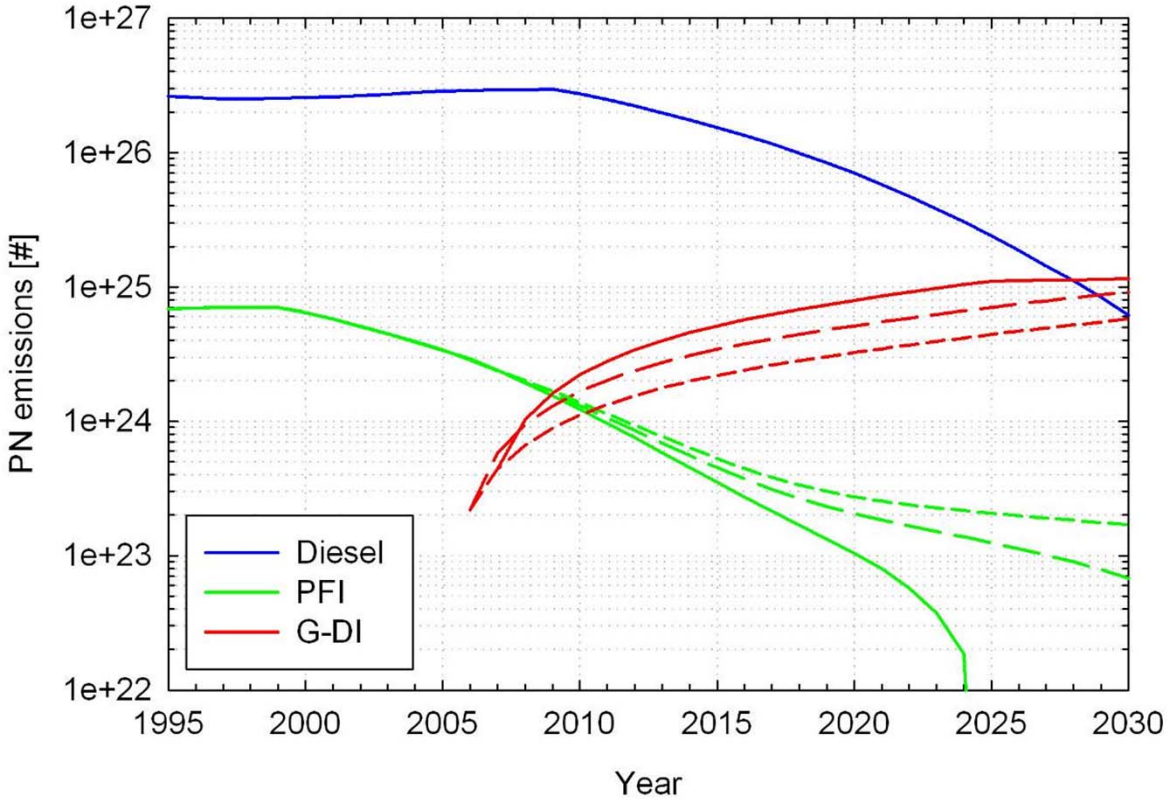
(JRC, Athanasios Mamakos, Giorgio Martini, ongoing work)



Effects on air quality

Effect of PIDI on air quality if no PN emission limit is introduced?

(JRC, Athanasios Mamakos, Giorgio Martini, ongoing work)

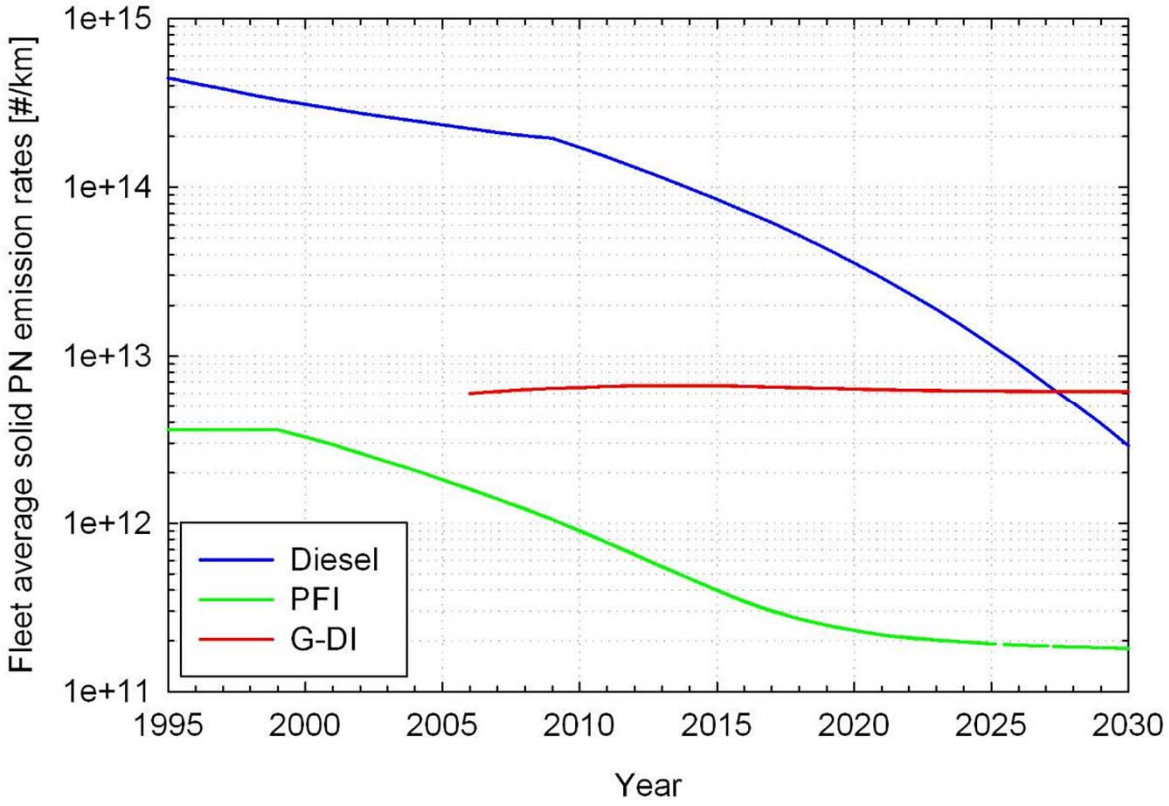


Evolution of solid PN emissions from PC and LDV in Europe according to the baseline scenario. The three different line types correspond to the different projections of G-DI market share.

Effects on air quality

Effect of PIDI on air quality if no PN emission limit is introduced?

(JRC, Athanasios Mamakos, Giorgio Martini, ongoing work)



Evolution of fleet average solid PN emission rates for the three main vehicle categories under the baseline scenario.

First conclusions

- **Focus of imminent legislation on PIDI**
- **Further research needed (not considered for imminent legislation but possibly later):**
  - "Off-cycle" (driving pattern, ambient temperature,…) PN emissions of PIPF, in particular for rich air/fuel ratios
  - PMP cutoff for small particle sizes of 23 nm: to be revised for PI?
  - Chemical composition/size spectrum of PI particle emissions: are there "specific" health issues?

PN abatement: technology & costs

Questionnaire & workshop with 8 GPF suppliers March 2011:

- Almost all OEMs investigate GPF at several implementation stages
- Engineering target of PN emissions < 6 x 10^{11} #/km can be met easily
- Fuel consumption penalty: not measurable on NEDC, ~1% under extreme high load motorway conditions
- OEM target is no active regeneration. If needed achieved by post-injection
  - Lean burn: always sufficient oxygen available
  - Stoichiometric: regeneration at fuel cut and high exhaust temperature.

    Good test results for "natural" driving profiles.

    But: extended driving at high load?
- Costs for system integration in vehicle estimates (by COM): 40 – 130 € depending on engine size, production volume and packaging (underflow vs. closed coupled)
- OEM lead time: about 3 years

PN abatement: technology & costs

Gasoline Particle Filters (GPF):

- Ceramic wall flow filter to remove airborne particles from the exhaust
- High exhaust temperatures, low concentration & high combustibility of PI soot => passive regeneration (?) and smaller GPF volume (compared to DPF)

Packaging options:

- Underfloor GPF
- Closed coupled with 3WC:
  - two bricks for GPF & 3WC
  - single brick for GPF & 3WC

Issues:

- Stoichiometric operation, urban driving => regeneration?
- Fuel consumption penalty
- Filtration efficiency at "empty" state
- System costs

PN abatement: technology & costs

Internal engine measures:

- Substantial reduction of PN emissions possible by optimising injection/ignition parameters and injector geometry
- Various major suppliers' projects based on engine calibration & "hardware" modifications; focus on cold start PN abatement
- PN emissions < 6 x 10^{11} #/km seem to be achievable on NEDC with "sufficient" lead time for a wide range of applications

However:

- Compromises on other objectives, such as fuel efficiency, may be necessary
- Off-cycle performance expected to become a big issue, e.g. stoichiometric/stratified combustion on test cycle / "real driving"

Further investigation necessary (autumn 2011):

- Technologies, lead time
- Costs: system (implementation, R&D) and "compromise" (e.g. fuel penalty)

PN abatement: health benefits

Marginal external costs (MEC) of PN emissions of PI not directly available**!**

⇓

Calculate MEC of PN emissions of PI from MEC of diesel soot

(= solid fraction of diesel exhaust)

Assumptions:

1) PN is a good metric for describing health damage (at least as good as PM)
2) Same PN quantities emitted by PI and CI are equally hazardous irrespective of the mean particle size and chemical composition

NB: Given the relatively small particle sizes and a potentially more hazardous chemical composition and shape of PI emissions (as compared with black carbon), assumption 2) can be considered as conservative in the light of today's scientific knowledge, effectively defining a lower bound for the MEC of PN emissions of PI

PN abatement: health benefits

Number of particles contained in diesel soot ???

- Estimate from log-normal size distribution: 1 to 8 x 10^{18} #/kg
  (log-average: 2,8 x 10^{18} #/kg)
  CARB estimate: 2 – 3 x 10^{18} #/kg

"Average" life time PN emissions of recent PIDI vehicles:

- 160 000 km x (7,6 x 10^{12} #/km) = +/- 1,2 x 10^{18} #/km

Marginal external costs (MEC) of diesel soot

- Epidemiological studies > 10 years
- Complex issue: PM sources, exposure of people (emissions -> immissions & exposure), health impacts, monetary valorisation, … => strong local dependence (population density, etc.)

PN abatement: health benefits

Cost estimates:

Source	Costs / kg	Costs for average PIDI lifetime PN emissions
Euro 5 impact assessment, EU average	26 – 75 € (primary PM)	11 – 32 € ???
Euro 5 impact assessment, Benelux	180 € (primary PM)	77 € ???
UK department for Environment	10 – 125 £ (primary PM)	4 – 54 £ ???
Swiss study (derived from P10), using WTO data	860 - 2300 CHF (diesel soot)	369 – 985 CHF

Conclusions & to-dos

- **Today's PIDI have PN emission limits of the order of 10^{13} #/km**
- **Euro 5/6 CI PN emission limit 6 x 10^{11} #/km ⇔ almost total PN abatement**
- **Almost total PN abatement of PIDI: GPF technology available**
- **A simple, conservative cost/benefit estimate shows that health benefits are in the same range as GPF cost estimates**

Conclusions & to-dos

- **Further steps:**

  - More sophisticated traffic and vehicle category simulation, but probably no strong influence on conclusions

  - Better estimate of diesel soot MEC

  - Most important: more precise assessment of diesel PN/soot ratio

  - (specific health hazards from PIDI PN emissions)

  - (PMP PN measurement procedure: lower cutoff?)

Conclusions & to-dos

- **Internal engine measures have potential for significant PN abatement**

  - Technical details & associated costs to be analysed: consultation of industry (questionnaires, workshop in autumn 2011)

  - Internal engine measures could lower costs for achieving "almost total PN abatement" significantly

  - Internal engine measures could suggest an "intermediate" PN emission limit for PIDI above current CI PN emission limit

Conclusions & to-dos

- **Lead time**

  - to be discussed with stakeholders

  - full introduction of ambitious emission limit at mandatory Euro 6 dates difficult, therefore

  - "final" PN emission limit gradually applicable to increasing share of the new vehicle fleet or

  - 2 step approach

- **"Off cycle" PN emissions**

  - a robust method to assess real driving PN emissions of PIDI will be necessary, at least if internal engine improvements are a regulatory option

Politics

- Some Member States (e.g. DE, NL) strongly support "PI = CI" PN emission limit (6 x 10^{11} #/km)
  - technology neutral
  - prudence principle
  - best available technique
- Other Member States put strong emphasis on costs of PIDI
- ACEA suggests PIDI Euro 6 PN emission limit of 6 x 10^{12} #/km (i.e. PI-limit = 10 x CI-limit)
- (CARB, LEV III: "optional" PN emission standard for PIDI of about 10^{12} #/mi is being considered)

Thank you!

Thank you for your attention!

Dr. Nikolaus Steininger
Automotive Industry Unit
Enterprise and Industry Directorate-General
European Commission
nikolaus.steininger@ec.europa.eu

More information: http://ec.europa.eu/enterprise/sectors/automotive/index_en.htm