Testing of soot sensors for DPF failure monitoring

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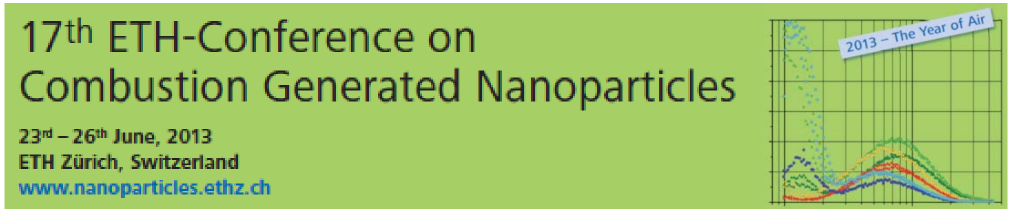


Contents

Objectives of the project

- Assess the technical feasibility of:
  - Euro VI OBD threshold limits (OTL)
- Evaluate especially DPF failure behaviour and the ability of current technologies to diagnose the actual status of a DPF
- Develop benchmarking measurement protocols and evaluate soot sensors with respect to PM and PN emissions

Euro VI OBD threshold limits
(EU Commission Regulation No 582/2011, 25 May 2011)

Values in mg/kWh	NOx (mg/kWh)		PM (mg/kWh)	CO (mg/kWh)
	PI	CI	CI	PI
phase-in period	1500		25	[tbd]
general requirements	1200		25	[tbd]

Phase-in period: 01.09.2014 (all vehicles: 01.09.2015)
General requirements: 31.12.2015 (all vehicles: 31.12.2016)

Final Euro 6 OBD threshold limits
(EU Commission Regulation No 459/2012, 29 May 2012)

		Reference mass (RW) (kg)	Mass of carbon monoxide (CO) (mg/km)		Mass of non-methane hydrocarbons (NMHC) (mg/km)		Mass of oxides of nitrogen (NOx) (mg/km)		Mass of particulates (PM) (mg/km)		Number of particles[1] (PN) (#/km)	
Category	Class		PI	CI	PI	CI	PI	CI	CI	PI	CI	PI
M	—	All	1900	1750	170	290	90	140	12	12		
N_1[3]	I	RW ≤ 1305	1900	1750	170	290	90	140	12	12		
	II	1305 <RW ≤ 1760	3400	2200	225	320	110	180	12	12		
	III	1760 < RW	4300	2500	270	350	120	220	12	12		
N_2	-	All	4300	2500	270	350	120	220	12	12		

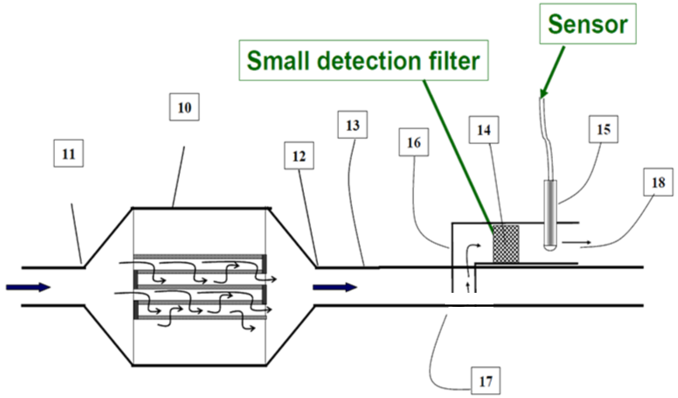
To be assessed by 1/9/2014

Implementation dates: M1 and N1/I: 1.9.2017/1.9.2018 New types/New vehicles
Implementation dates: N1/II, III and N2: 1.9.2018/1.9.2019 New types/New vehicles

Contents

Soot sensor manufacturers

- Bosch (resistive)
- **Continental** (resistive)
- Delphi (resistive)
- General Electric Accusolve (radio frequency)
- **Electricfil** (resistive)
- Emisense - Watlow (particle charge)
- **Innexsys** (detection filter, temperature sensor)
- NGK (impedance sensor)
- **NTK** (particle charge)
- Sensata / Sensor-NITE (resistive)
- **Stoneridge** (resistive)



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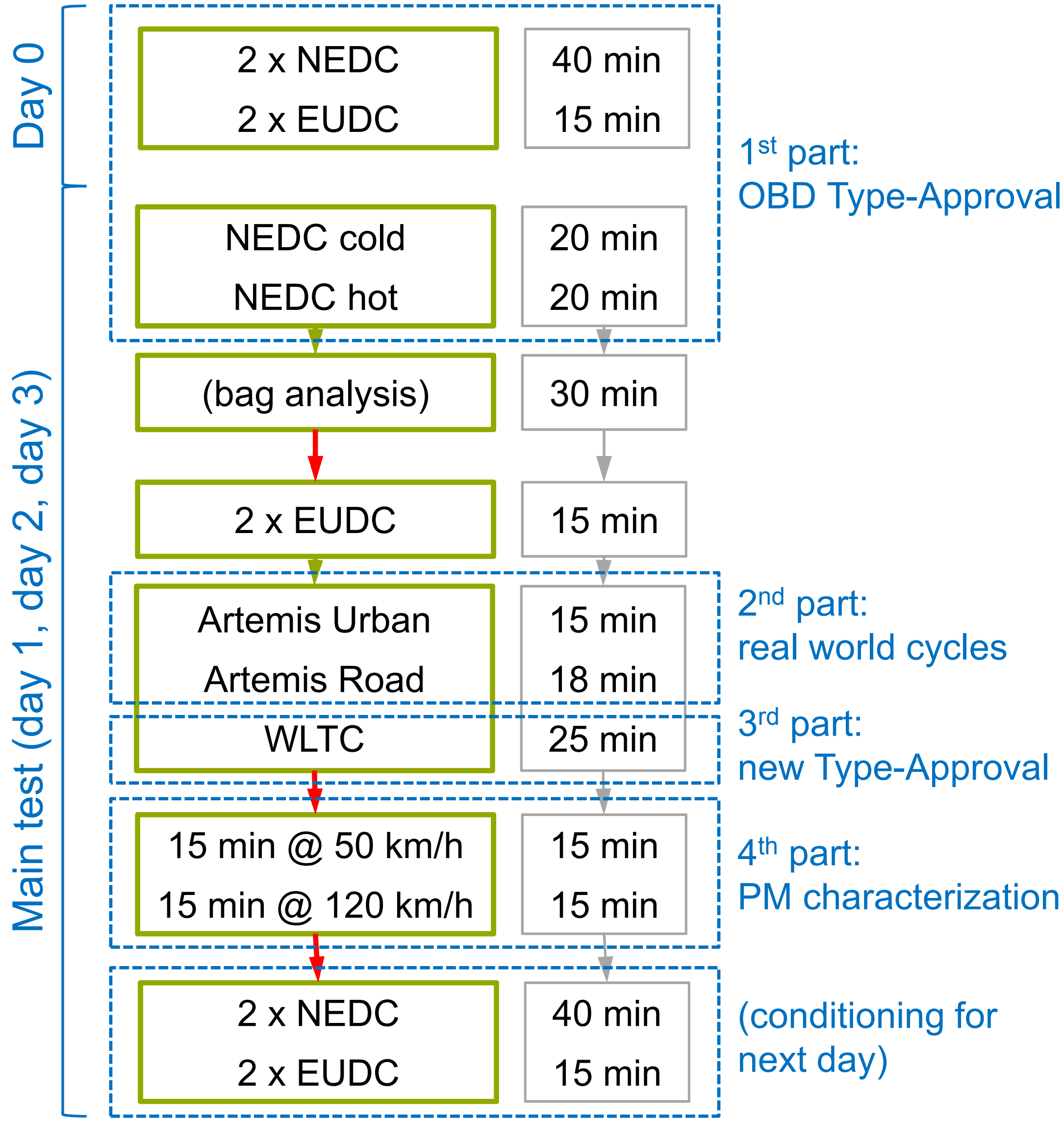
Benchmarking test protocol

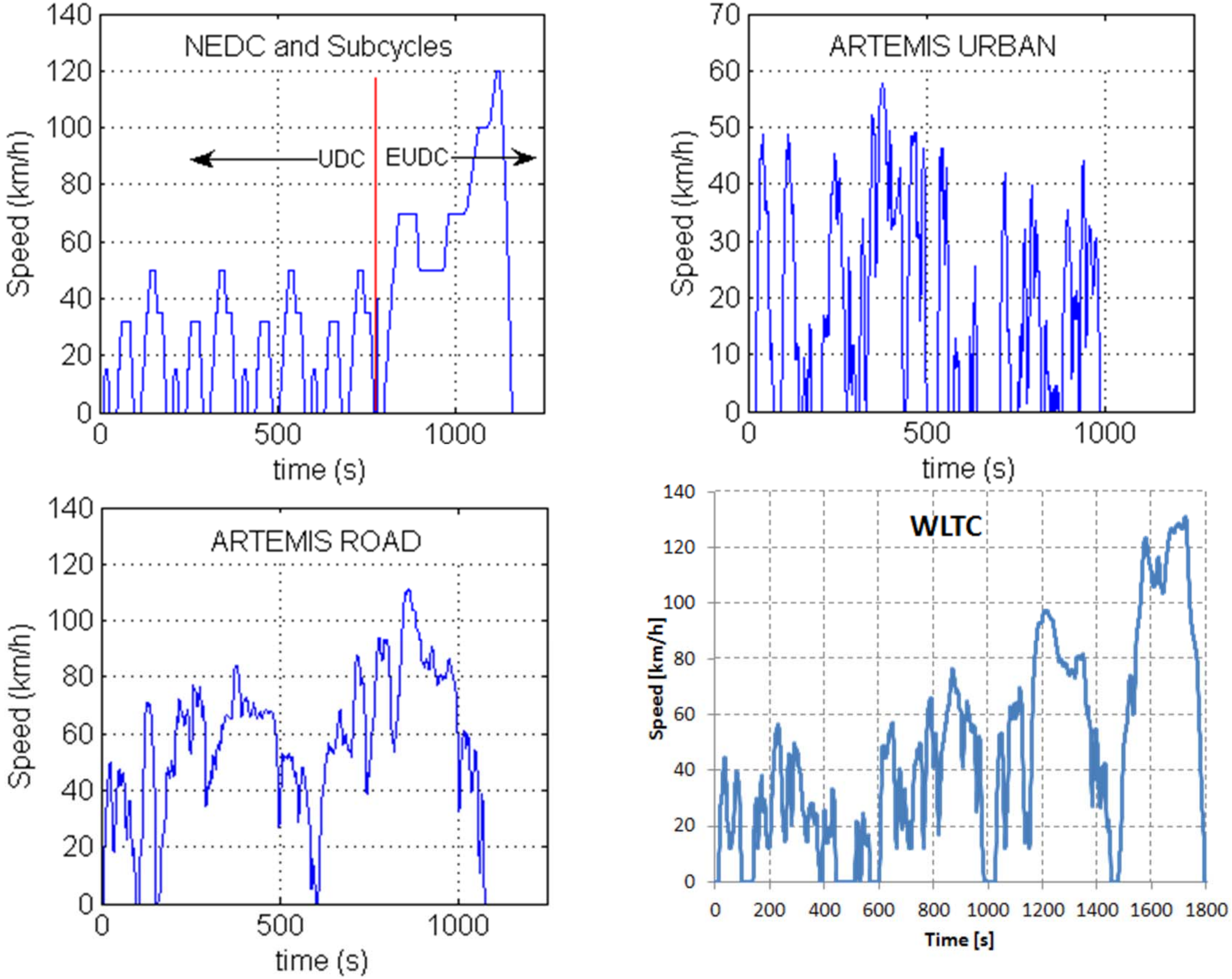
- The benchmarking protocol specifies:
  - Measurement protocol including preconditioning, drive cycles etc.
  - Measurement instrumentation (PM and soot, engine operation)
  - Soot sensor use, installation in the exhaust system, data logging and communication
  - Post-DPF emission targets and DPF failure levels
  - Malfunction simulation method to physically modify DPFs to give elective levels of soot penetration and post-DPF PM emissions

- The protocol was developed on LDV and adjusted and extended to HDV

LDV daily test protocol



Driving Cycles (LDV)



HD E and V daily test protocol

Preconditioning
- Warm-up and passive regeneration of the DPF; Full Load — 20 min
- DPF Loading (hot start WHTC) — 30 min

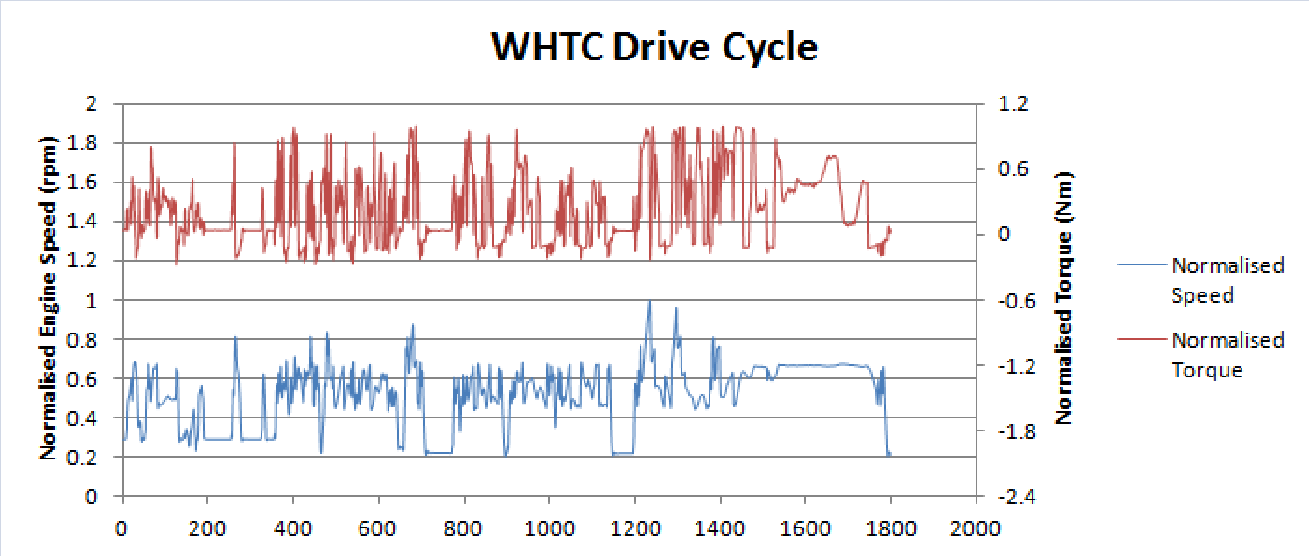
Eu IV Regulatoy test (repeated x3)
- Preconditioning 1200rpm; 50% throttle — 30 min
- hot-start WHTC test — 30 min

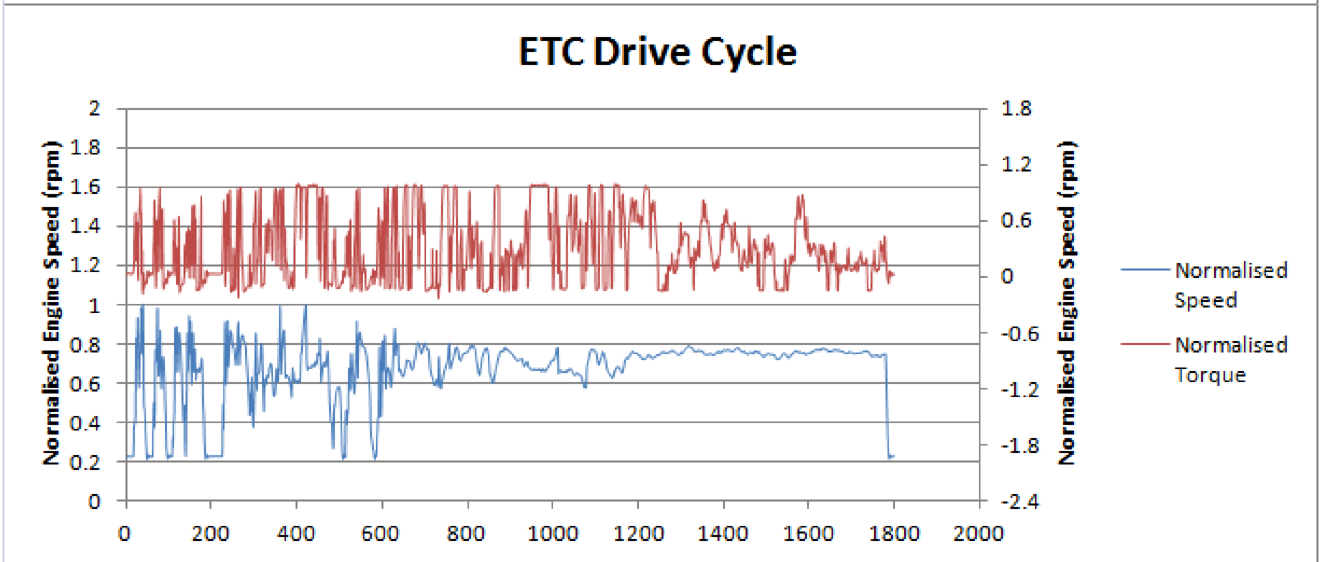
Low volatile PM
- WHSC Mode 2 Preconditioning — 10 min
- WHSC Mode 2 (Full Load) — 30 min
- WHSC Mode 2 (Full Load) — 30 min

Higher volatile PM
- WHSC Mode 12 Preconditioning — 10 min
- WHSC Mode 12 (Part Load) — 30 min
- WHSC Mode 12 (Part Load) — 30 min

Eu VI Regulatoy test (repeated x3)
- Preconditioning 1200rpm; 50% throttle — 30 min
- hot-start ETC test — 30 min

Driving Cycles (HD V and E)





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LD test vehicle specifications

- Honda Accord 2.2i-CTDi
- Engine: 4 cyl., Common rail, DI
- Capacity: 2200cc
- Power: 100 kW
- Gearbox: Manual
- Certification: Euro 4

- Original aftertreatment:
  - EGR
  - Oxidation pre-catalyst
  - 2-stage DOC with DeNOx characteristics ("4-way catalyst")

- Possibility to replace underfloor catalyst with DPFs of various sizes

DPF and sensor arrangement in the exhaust line (LDV)

Engine → Exhaust

Test DPF (T, Dp)

3 "resistive" sensors

“bypass filter" sensor

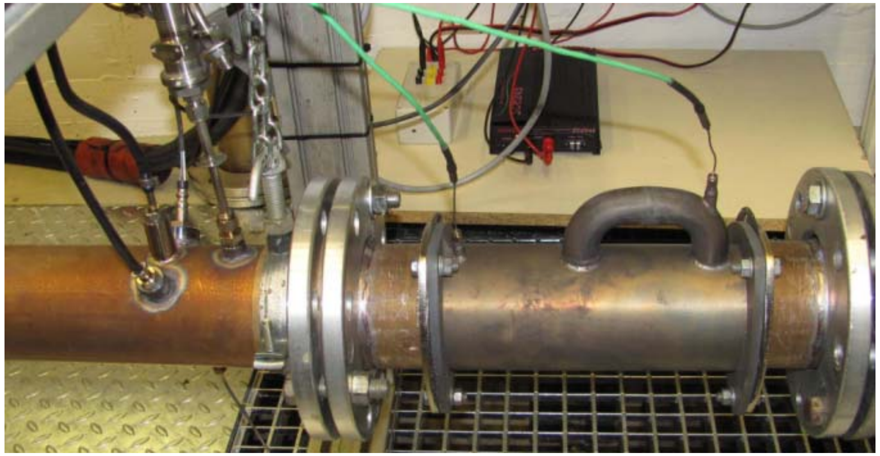
HD test engine and vehicle specifications

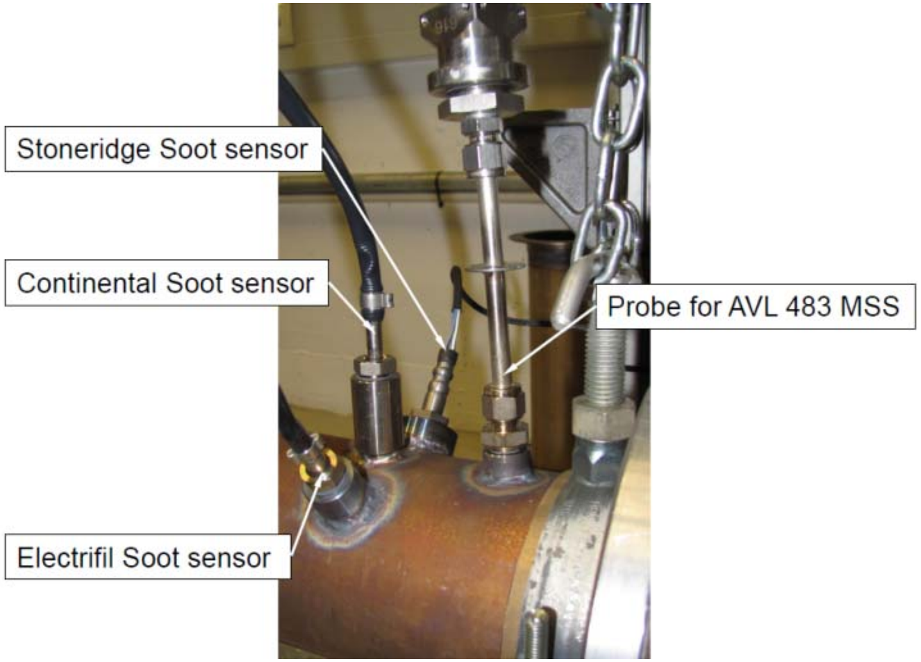
- MAN D2066 LF21
- Emission level: **Euro V**
- Capacity: 10 520 cm^3
- Rated power: 324 kW/1900 min^{-1}
- Rated torque: 2100 Nm/1000 min^{-1} to 1400 min^{-1}
- In original configuration equipped with a SCR System (removed for the tests)

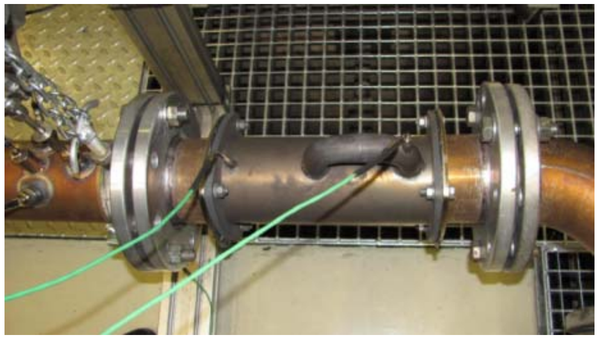
- Mercedes-Benz Actros **Euro VI**
- Gearbox: G 211-12 (ratios between 14,93 – 1,0) – MB Powershift
- Engine OM 471, R6, 12,8L, 310kW@1800rpm, 2100Nm@1100rpm
- Fleetboard connection

- Manufacturer: Daimler AG
- Model: OM 501 LA.III/5
- Emissions level: **Euro III**
- Engine / capacity: 11 946 cm^3, 290kW@1800 1/min, 1850Nm@1080 1/min
- OEM Emissions control system: DOC

DPF and sensor arrangement in the exhaust line (HDE, TUG)







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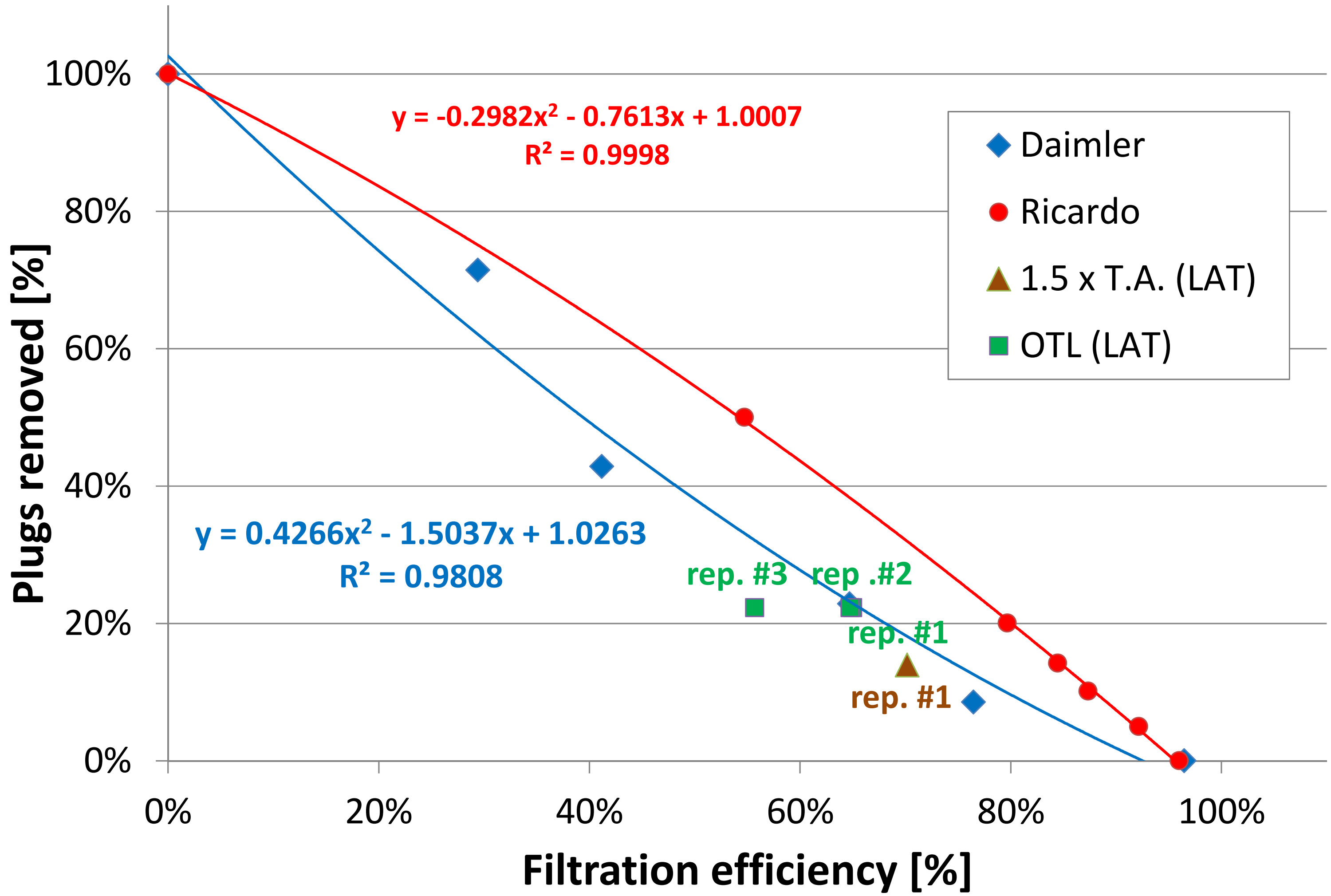
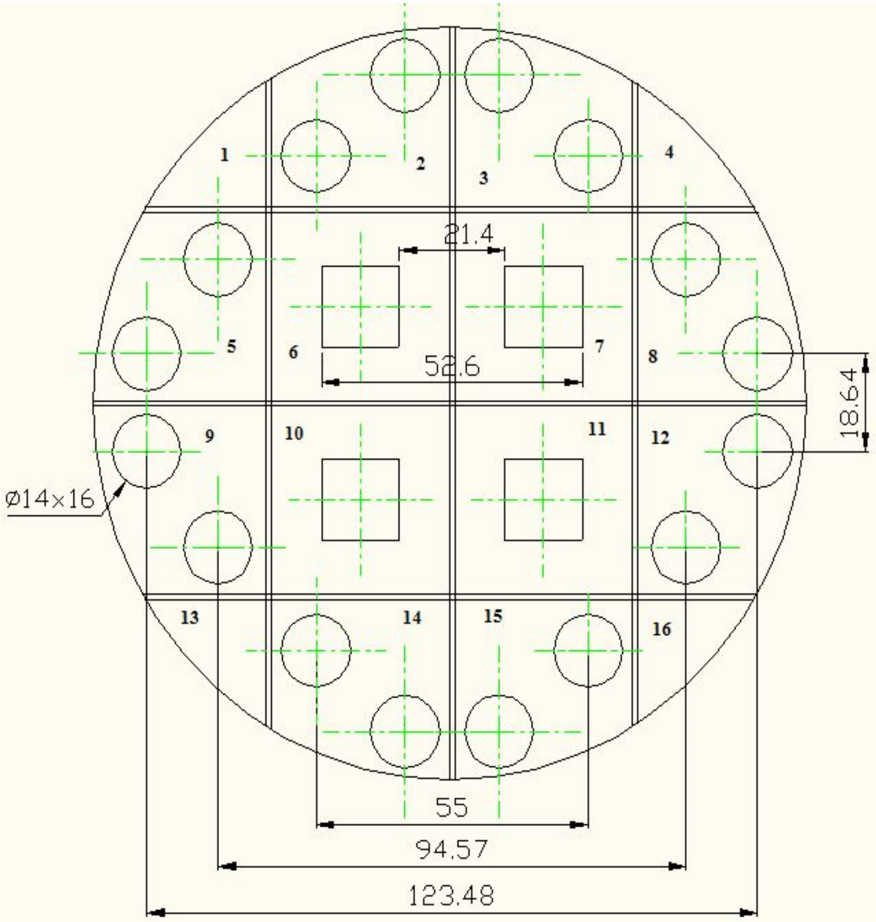
Failure levels simulated

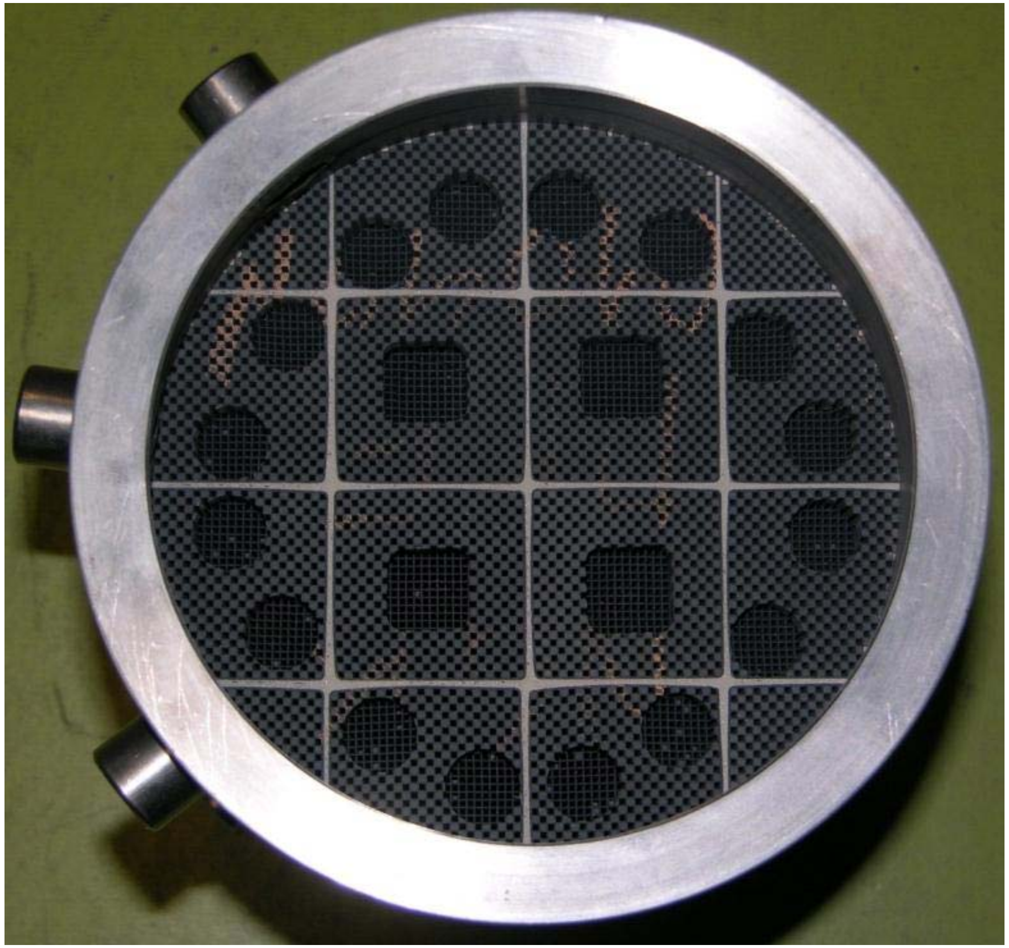
- The test cycle series will be driven using DPFs at the following failure status:
  - No DPF (engine out emissions)
  - DPF without failures (new DPF)
  - DPF artificially failed to reach Type-Approval limit PM emission level
  - DPF artificially failed to reach 1.5 x Type-Approval limit PM emission level
  - DPF artificially failed to reach OTL PM emission level
  - DPF artificially failed to reach > OTL PM emission level
- The filtration efficiency levels were not revealed prior to the completion of the first phase of evaluation by the sensor manufacturers.
- 50% of the filtration efficiency levels were revealed to the sensor manufacturers for calibrating the sensor models within the second phase of evaluation.

DPF failure response (LDV)



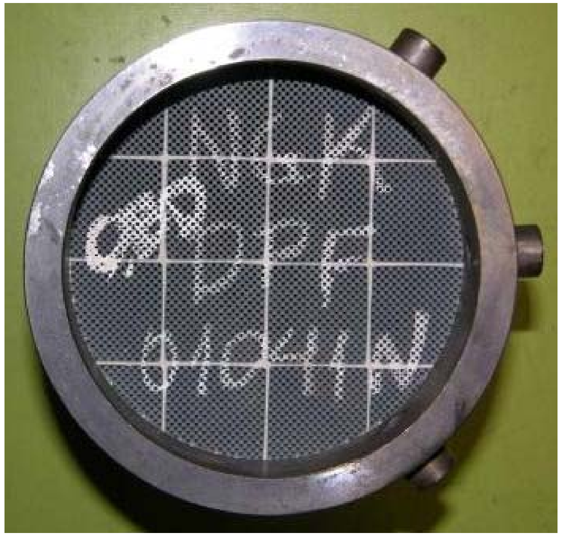
DPF failure LDV: "OTL" (target: 12 mg/km)
Plugs removed: 800 (22%)



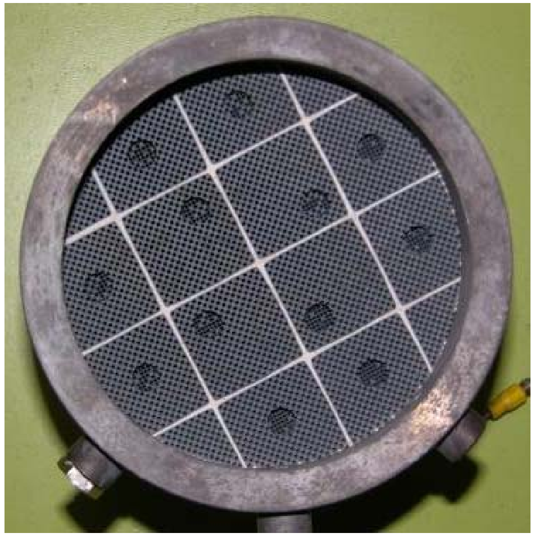


Failed DPFs (LDV)

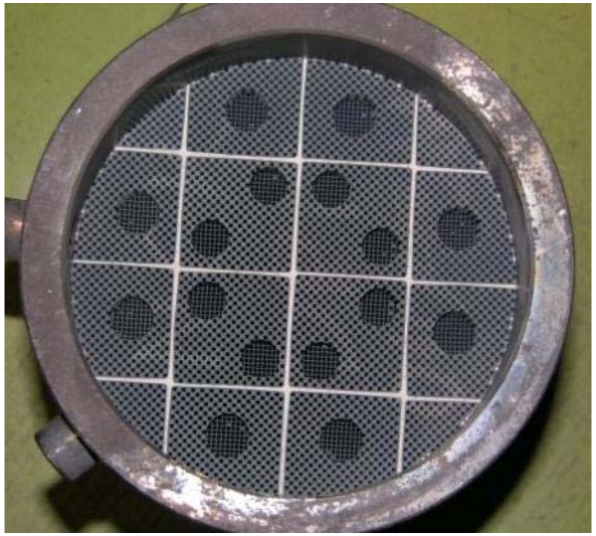
Full DPF



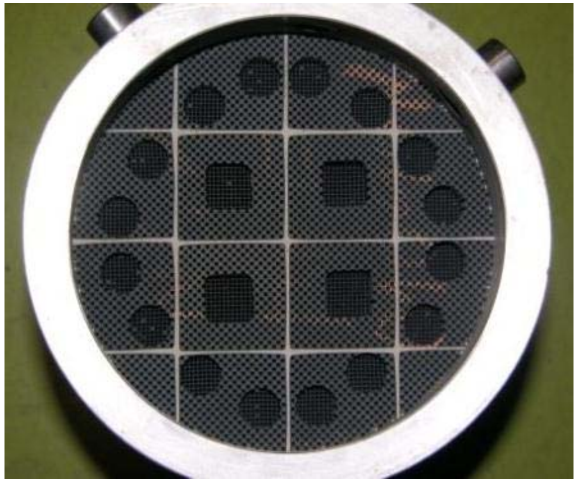
Type-Approval



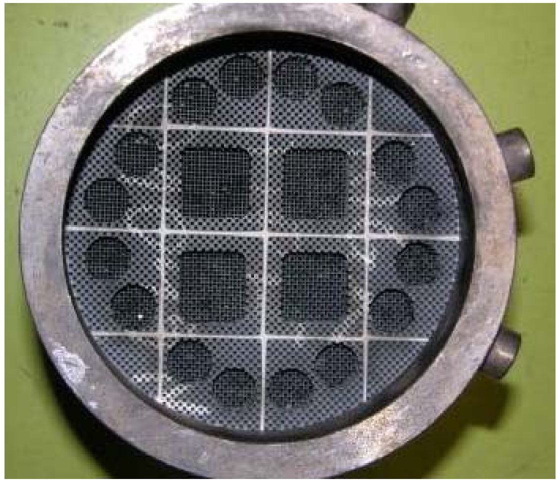
1.5 x Type-Approval



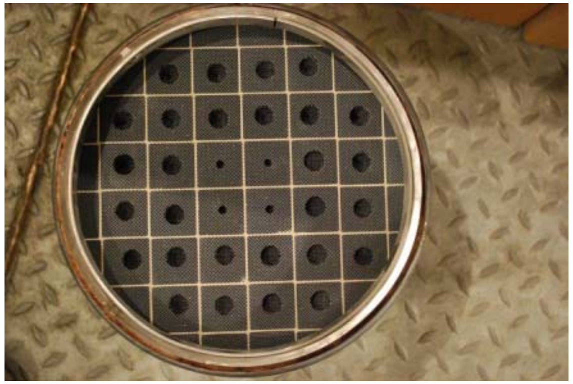
OTL

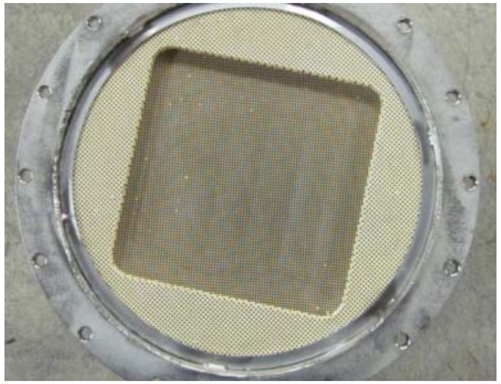


Above OTL



Failed DPFs (HDE)





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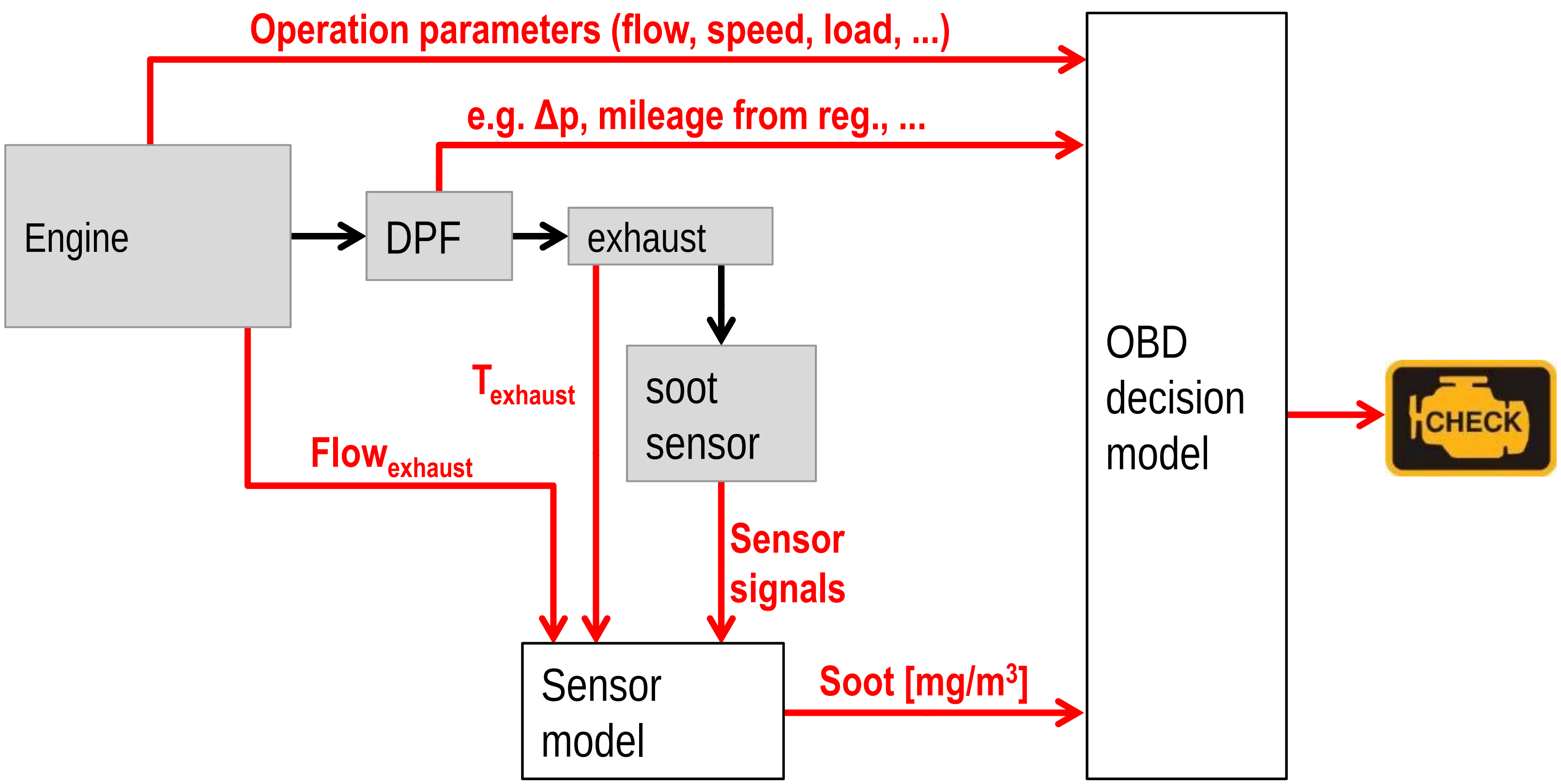
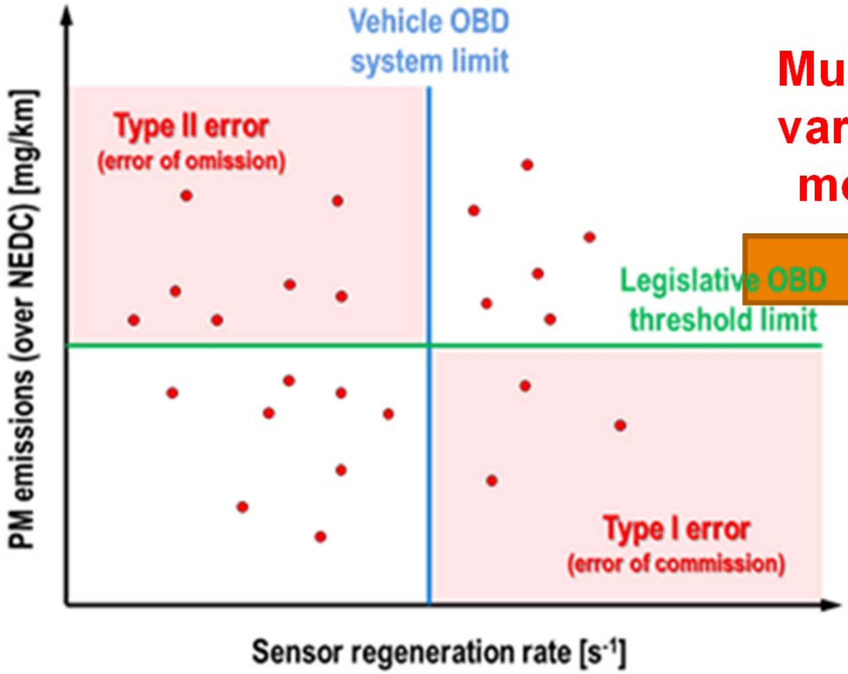
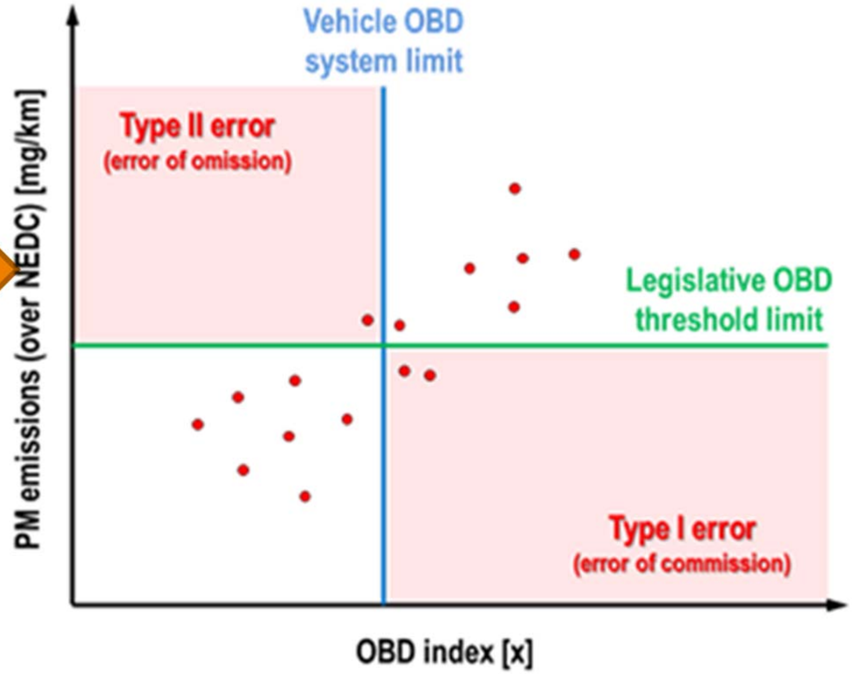
Integrated OBD modeling



OBD modeling target



Multiple variable model



Step 1

- A “good DPF” and a “bad DPF” are defined with an expected emission level below and above the OTL respectively

Step 2

- The variables that will be included in the Soot Index apart from the regeneration rate [1/(regeneration cycle time)] are identified

Step 3

- The “complete” regeneration cycles in the experimental results are isolated

Step 4

- A Soot Index function is calculated. To improve the quality of the results, a Box-Cox transformation may be used.

Contents

Results

- Figures 2 and 3 show the distributions for “good DPF” and “bad DPF” for LDV and HDV
- The Soot Index values for the “good DPF” and the “bad DPF” fit to a normal distribution

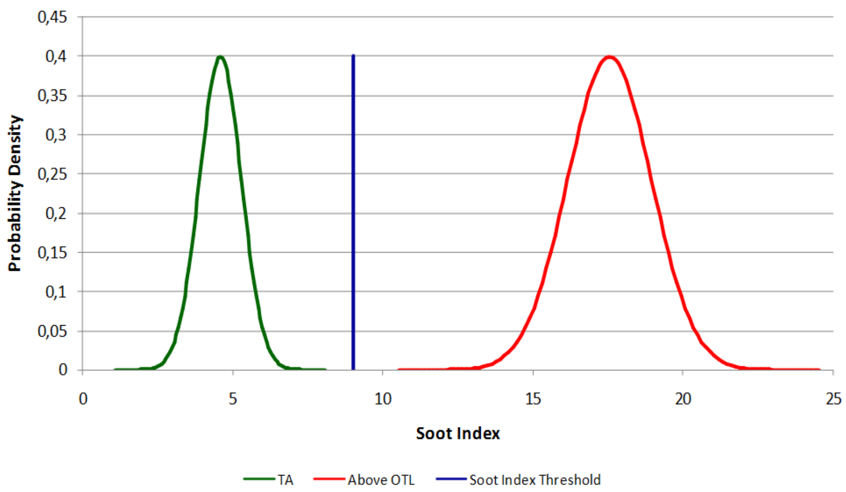


Figure 2: LDV

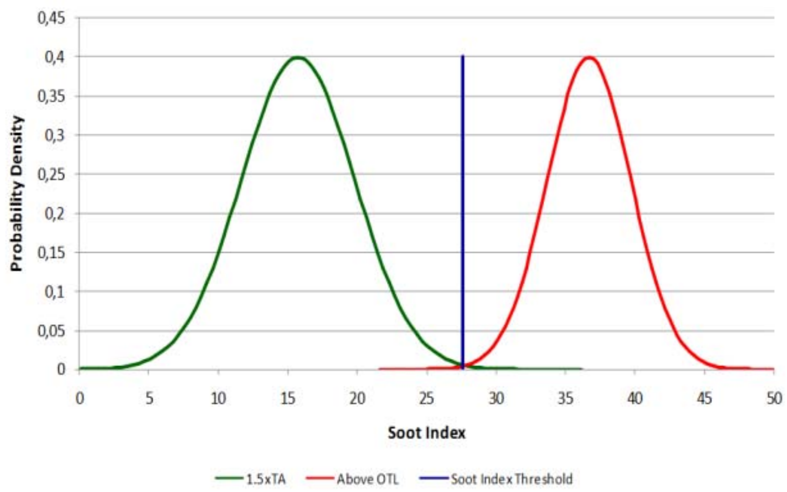


Figure 3: HDV

- A correct classification between “good DPF” and “bad DPF” is possible with Type I and Type II errors of less than 1% for both light and heavy-duty vehicles.

Overview of results of OBD OTL project

Sensor	Information		LAT (LDV)	TUG (HDE)	TNO (HDV)	JRC (HDE)
A	Type I + Type II error	Manufacturer	5%	0%	n/a	n/a
		Consortium	0%	0%	n/a	n/a
B	Type I + Type II error	Manufacturer	n/a	0%	0%	0%
		Consortium	0.3%	0%	0.3%	n/a
C	Type I + Type II error	Manufacturer	n/a	n/a	n/a	n/a
		Consortium	0%	2.9%	0%	4.9%
D	Type I + Type II error	Manufacturer	16%	n/a	13%	57%
		Consortium	0%	n/a	0%	n/a
E	Type I + Type II error	Manufacturer	n/a	n/a	0%	n/a
		Consortium	n/a	n/a	0%	n/a

Legend: Colour notation (evaluation of the sensor measurement by the manufacturer or the project consortium)

- Good performance
- Adequate performance and/or number of observations is too low to draw safe conclusions
- Inadequate evaluation

Contents

Objectives

Development of a benchmarking test protocol

- Soot sensors
- Test protocol and instrumentation
- Test vehicles
- DPF failure

Sensor evaluation

- Data assessment procedures
- Results

Conclusions

Conclusions (1 of 2)

- The resistive sensors A, B, C were found capable to produce a signal that can underpin the production of a statistical index which can be used for OTL exceedance detection.
- Sensor D is based on a promising and low cost principle of operation. There is more work though needed to improve the sensor ability to detect marginal DPF failures especially towards the definition of an OBD strategy model.
- Sensor E is a real time measurement instrument. This sensor is expected to perform well in combination with an advanced OBD model and a multivariate calibration.

Discussion on demonstrated sensor capabilities (2 of 2)

- A possible increase of the detection time or distance may allow better detection for already efficient sensors and adequate accuracy for currently less immature sensors.
- Sensor prototypes were faced with problems which are considered by the consortium as early childhood failures.
- **The OBD Threshold Limit for Heavy-Duty vehicles of 25 mg/kWh is technically feasible with the existing sensors,**

Thank you for your attention

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