www.sustainableroadfreight.org

Nanoparticle emissions from heavy-duty dual-fuel diesel and natural gas engines

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18th ETH-Conference on Combustion Generated Nanoparticles

23rd June 2014

Outline

- Introduction
  - What is dual-fuel?
- Experimental
- Results
  i. What effect does the dual-fuel conversion have on engine emissions?
  ii. Are there benefits for PM and other noxious gases?
  iii. Does it reduce total GHG emissions?
- Conclusions

Centre for Sustainable Road Freight

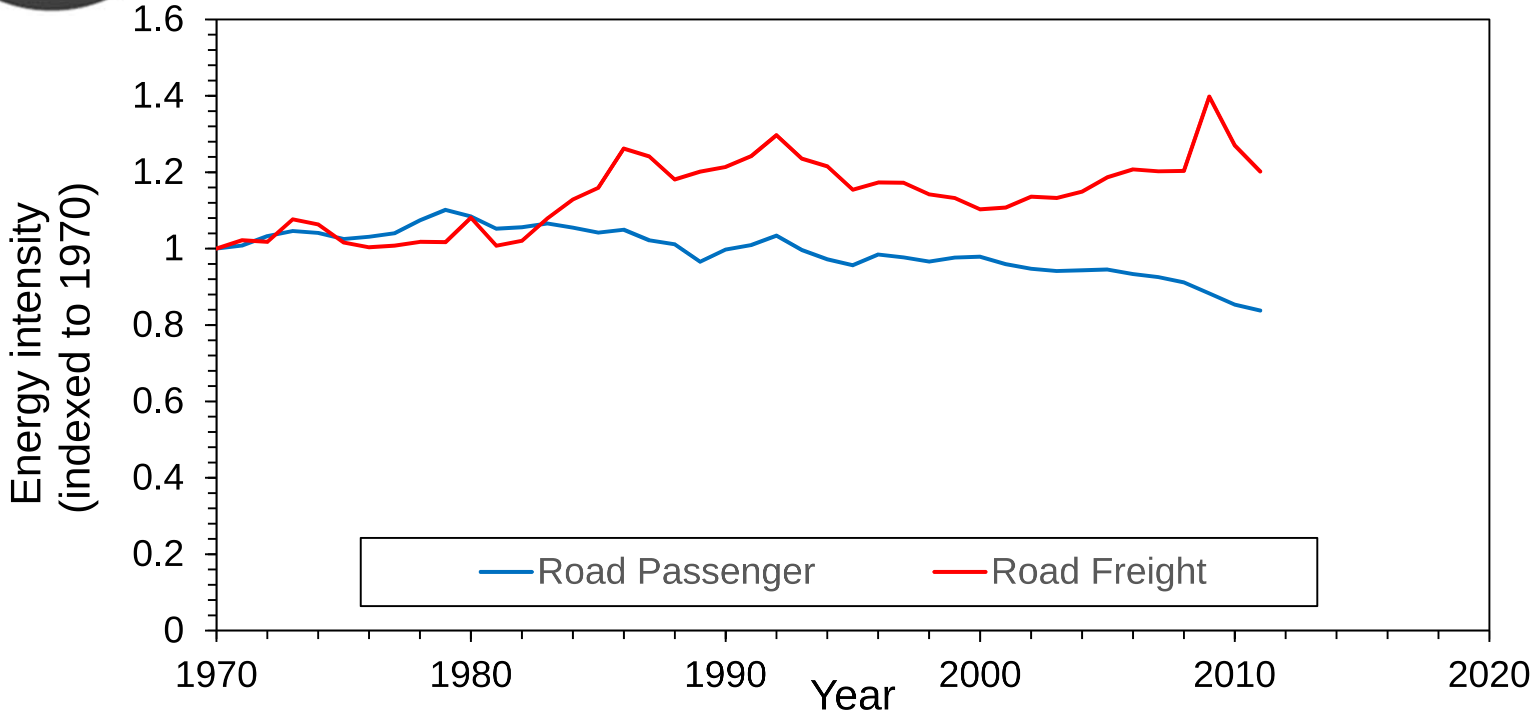
- Collaboration between Cambridge and Heriot-Watt Universities and organizations in the freight and logistics sectors, with a £5.8 million 5-year grant from EPSRC.
- www.sustainableroadfreight.org.uk

DHL GOODYEAR VOLVO LAING O'ROURKE Haldex

Chevron Coca-Cola Wincanton John Lewis DENBY

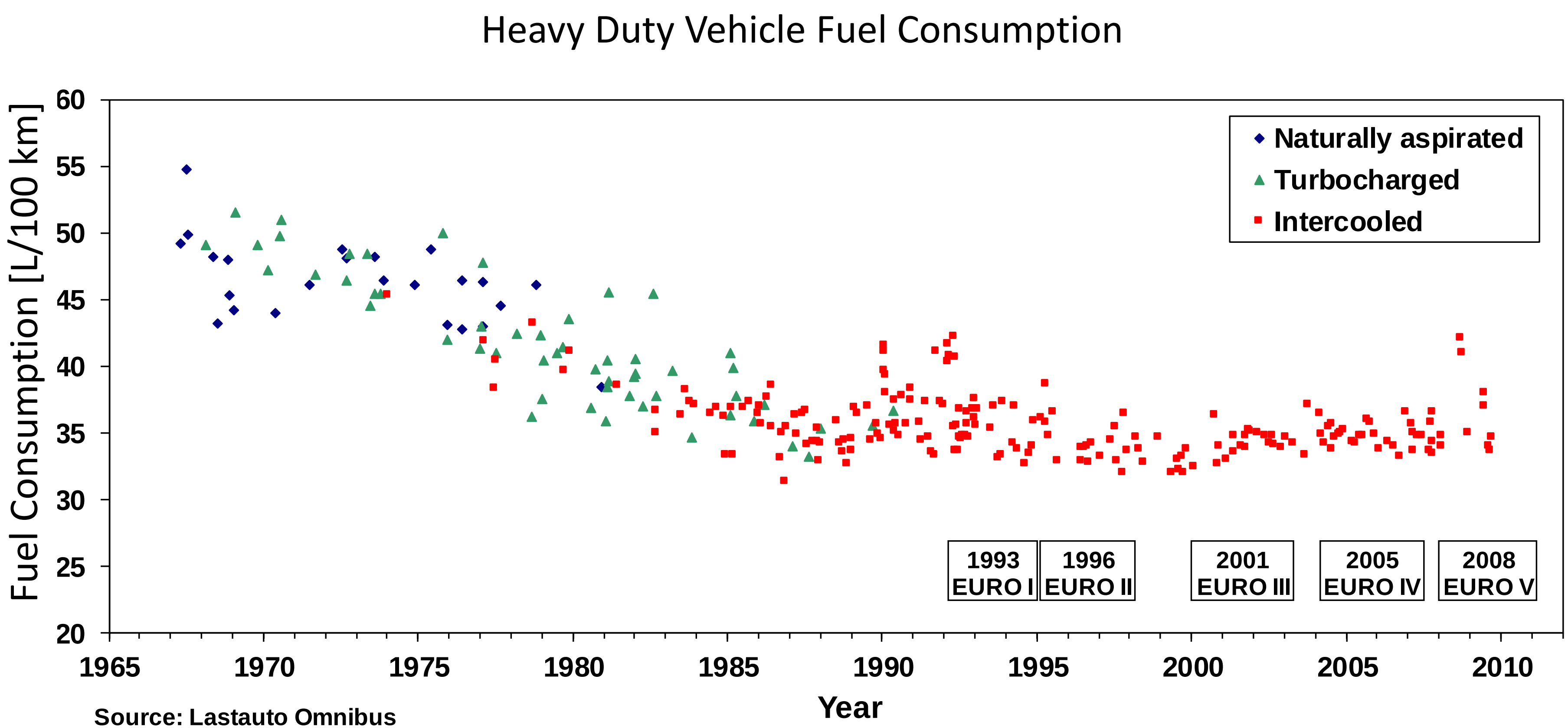
Warburtons OPTRAK VEHICLE ROUTING SOFTWARE TESCO FTA Freight Transport Association Delivering safe, efficient, sustainable logistics

UK transport energy intensity



- Freight accounts for 21% of transport energy use in UK (2012)
- Energy intensity is 20% higher than in 1970

Heavy duty vehicle fuel consumption



Source: Lastauto Omnibus Testberichte 1967 - 2009

Data Courtesy Daimler

No Change Since 1986

UK push to gas in freight

- 2009 UK's Low Carbon Strategy
- Ricardo-AEA report (2012):
  - Enable diesel engines to run dual fuel (diesel and natural gas)
  - 16-40% CO_2 reduction
  - Improvements in air pollution?
- UK Low Emission HGV Task Force
  - £9.5M government support
  - Vehicles and infrastructure

RICARDO-AEA

Opportunities to overcome the barriers to uptake of low emission technologies for each commercial vehicle duty cycle

Knowledge Transfer Networks

Transport

Department for Transport

The Chartered Institute of Logistics and Transport (UK)

SMMT DRIVING THE MOTOR INDUSTRY

FTA

RHA

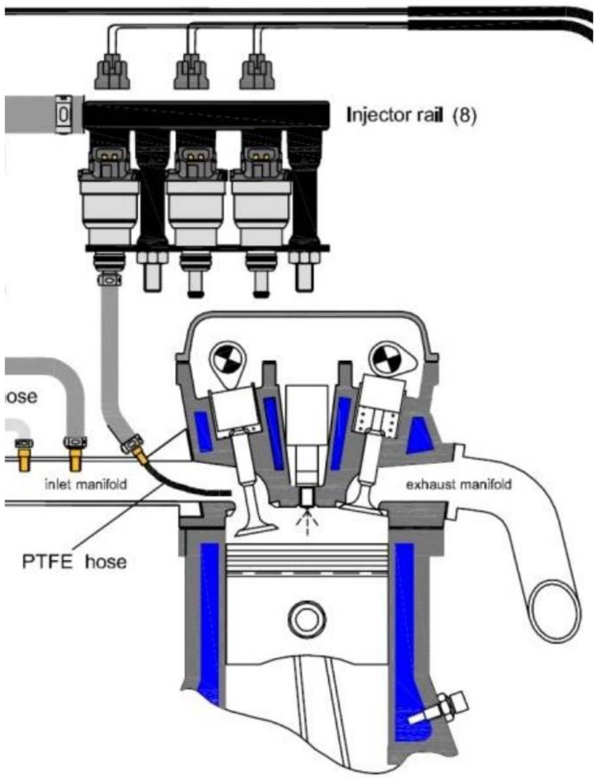
Report for the Task Force on Fuel Efficient, Low Emission HGV Technologies, funded by the Transport Knowledge Transfer Network and delivered through the LowCVP

Ricardo-AEA/R/ED58189
Issue Number 5
Date 30th November 2012

LowCVP
low carbon vehicle partnership

Dual-fuel conversion systems

- Prins Diesel-blend
- Aftermarket 'upgrade'



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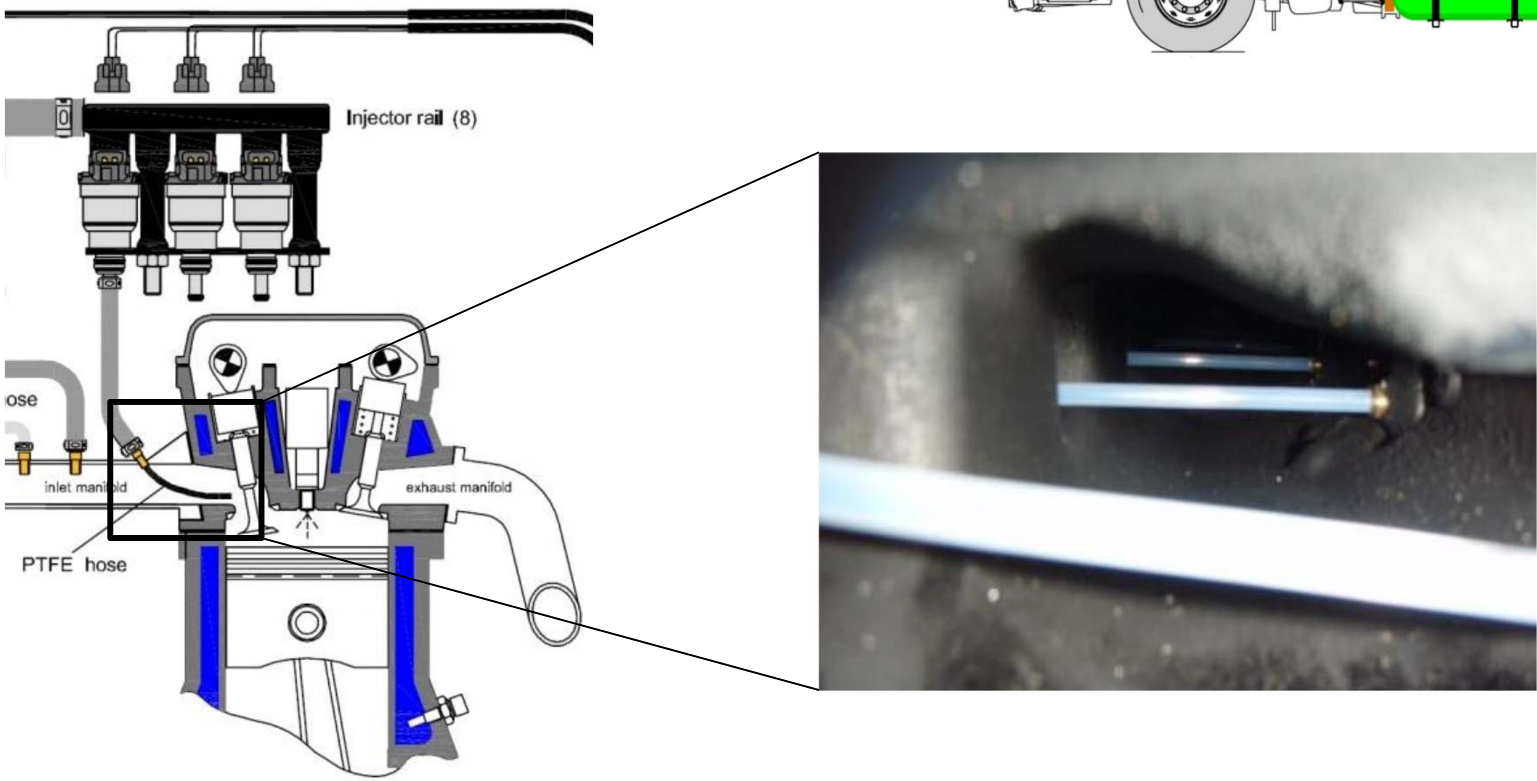

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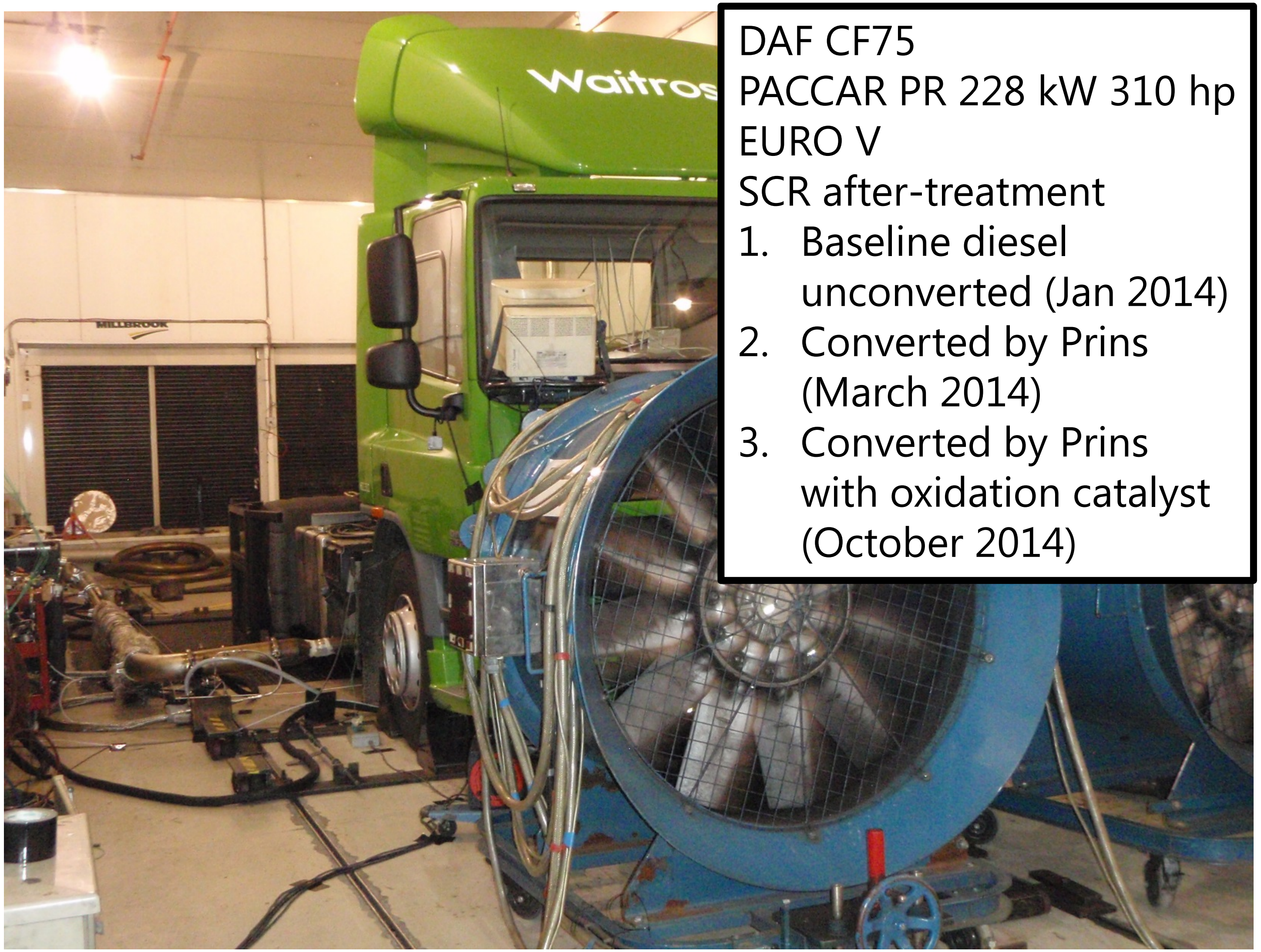
Engine emissions testing

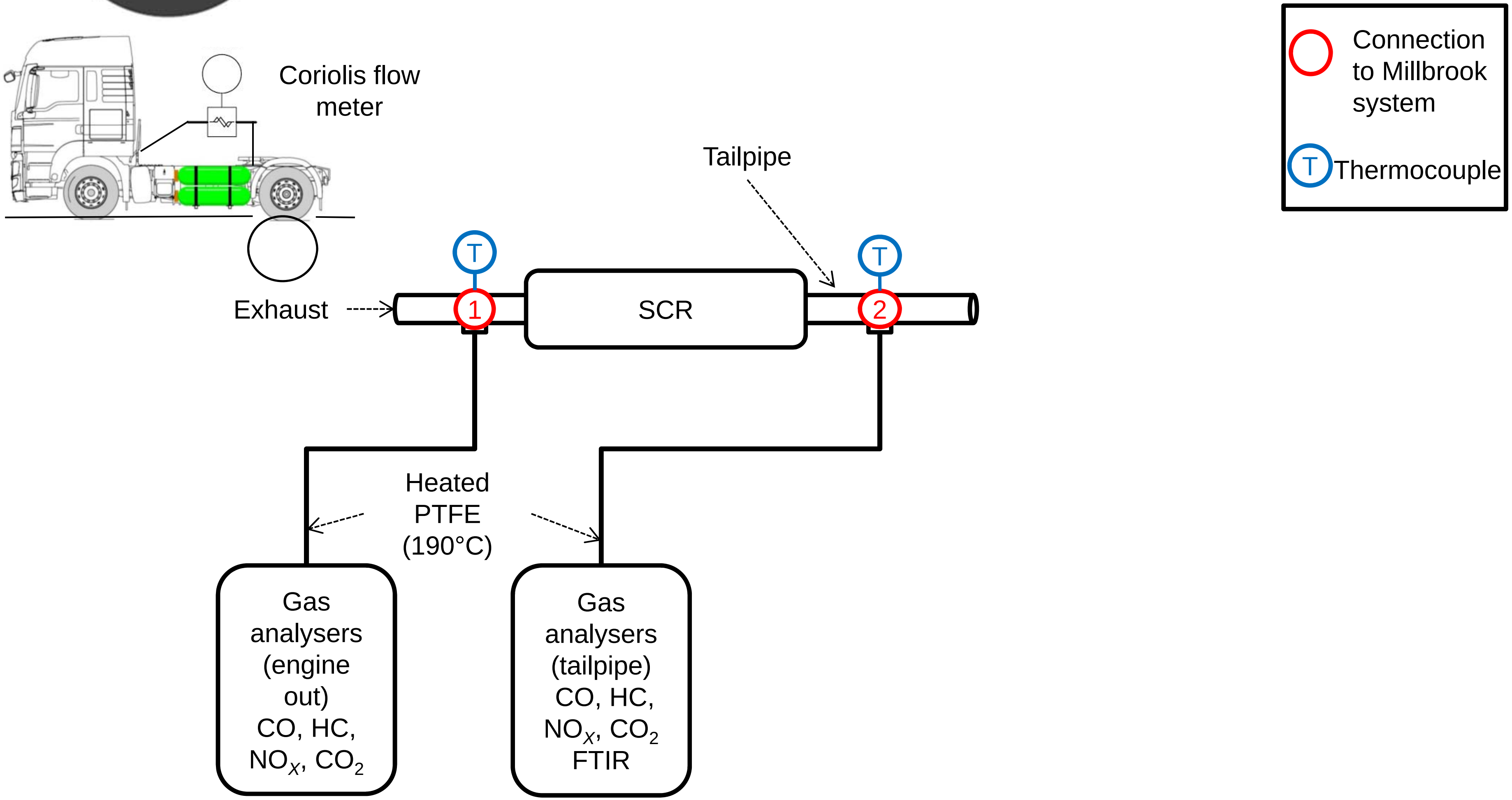
Engine emissions testing



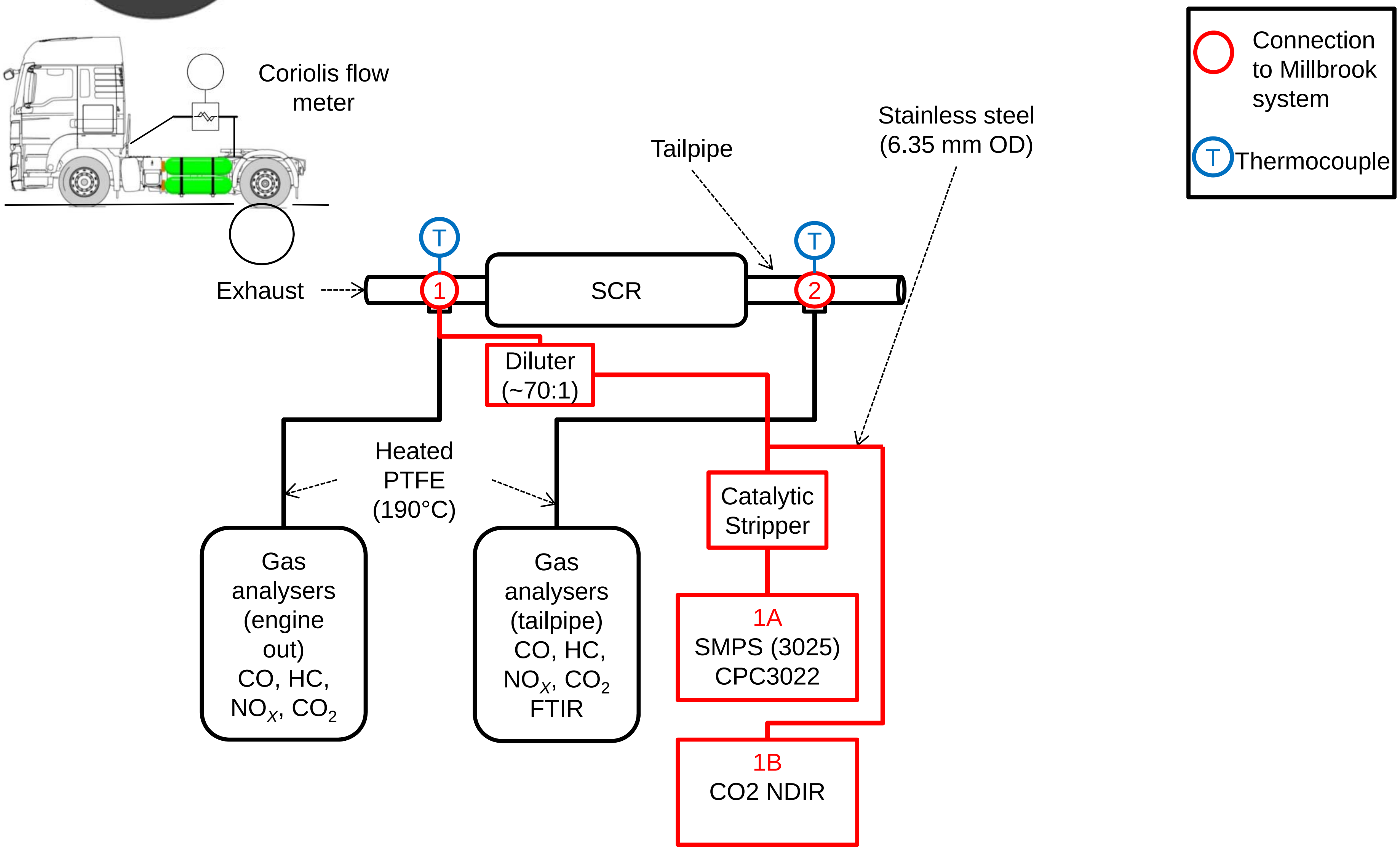
DAF CF75
PACCAR PR 228 kW 310 hp
EURO V
SCR after-treatment

1. Baseline diesel unconverted (Jan 2014)
2. Converted by Prins (March 2014)
3. Converted by Prins with oxidation catalyst (October 2014)

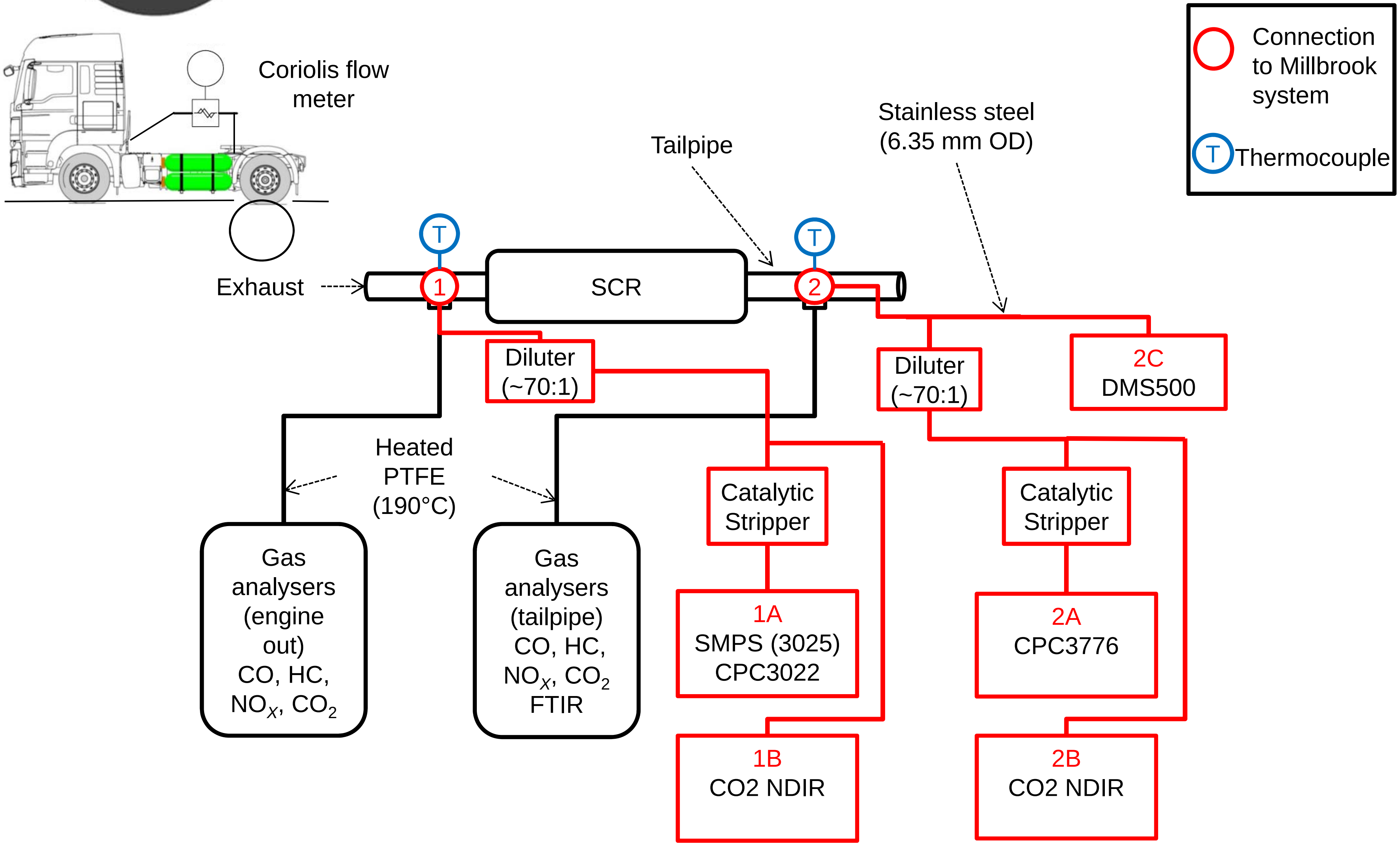
Experimental schematic



Experimental schematic

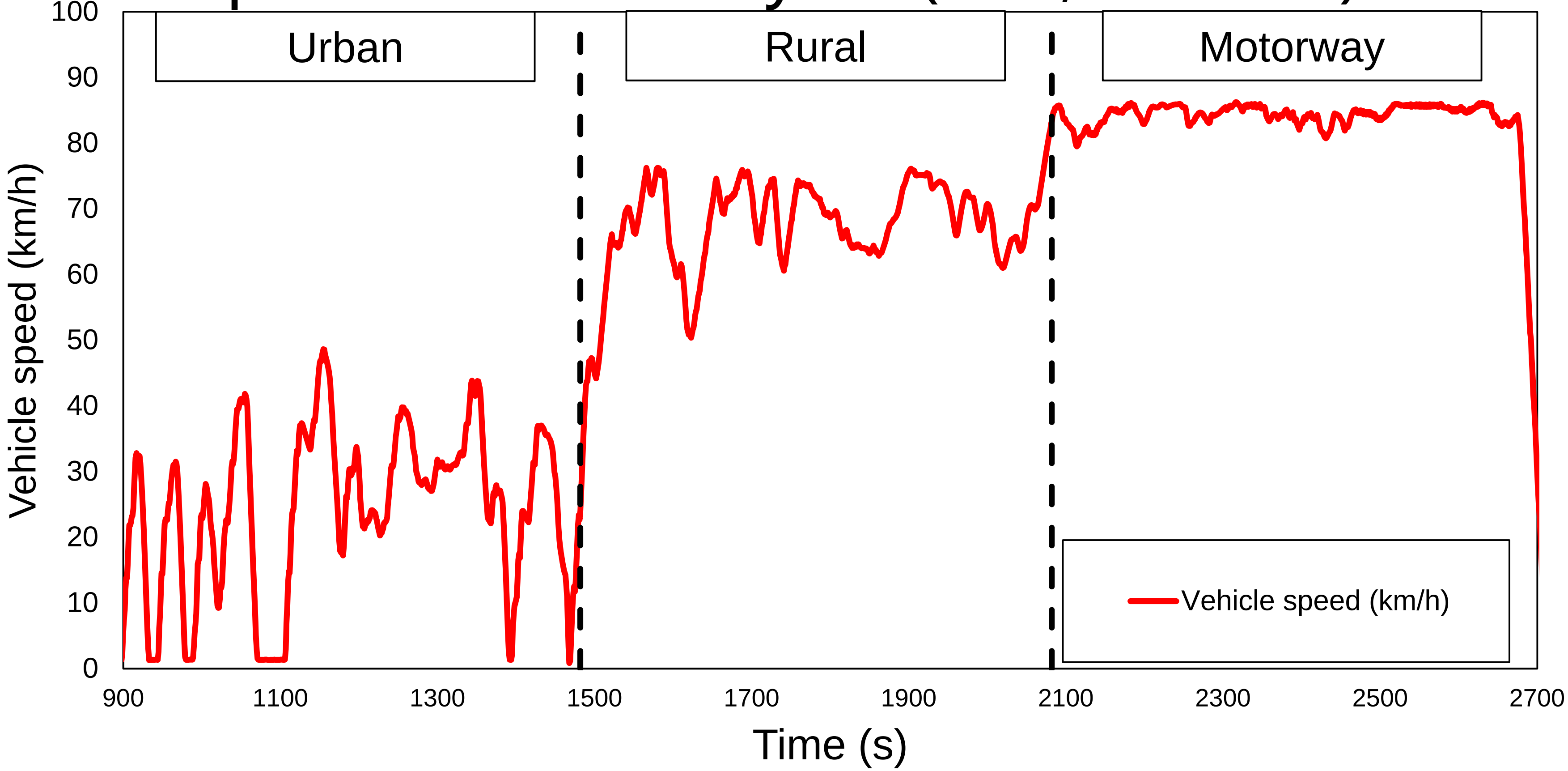


Experimental schematic



Test points

- Steady state
- European transient cycle (ETC, or FIGE)



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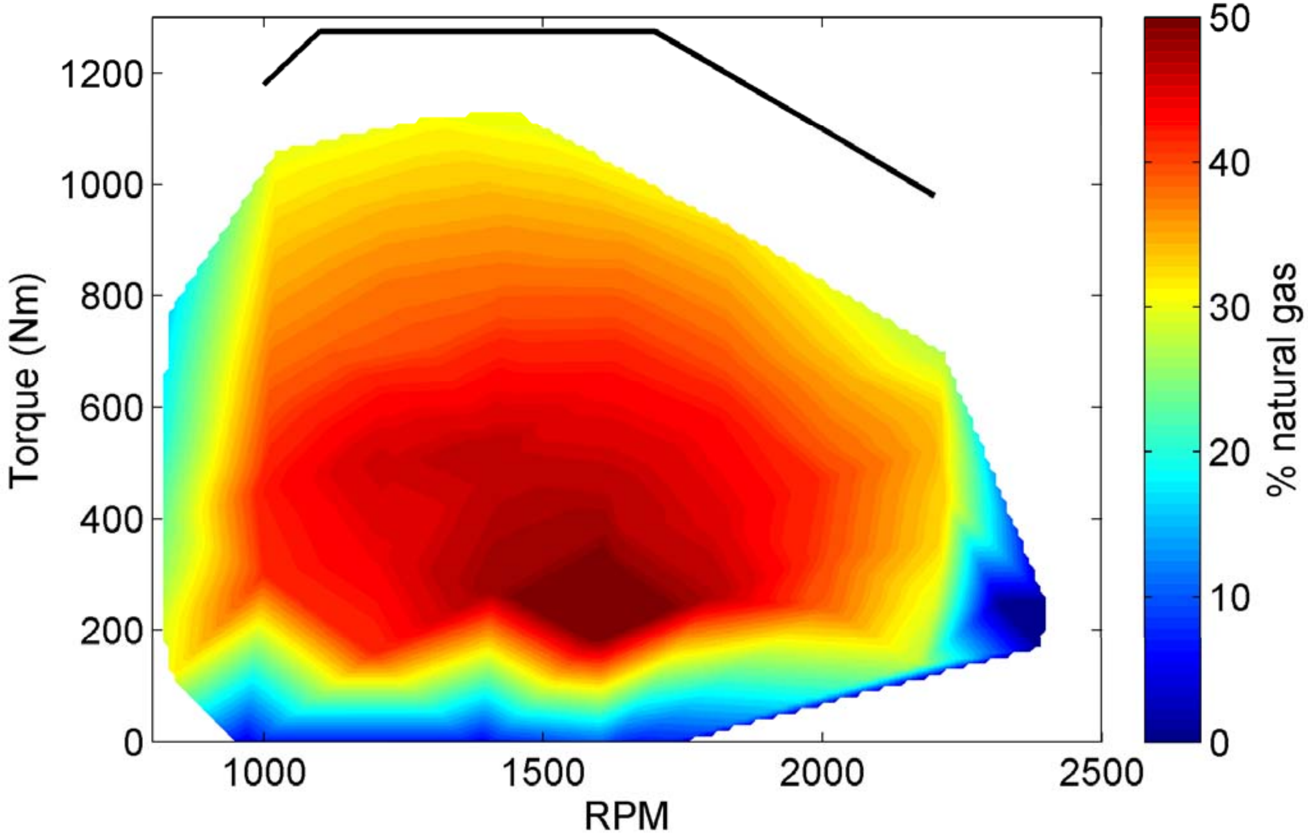
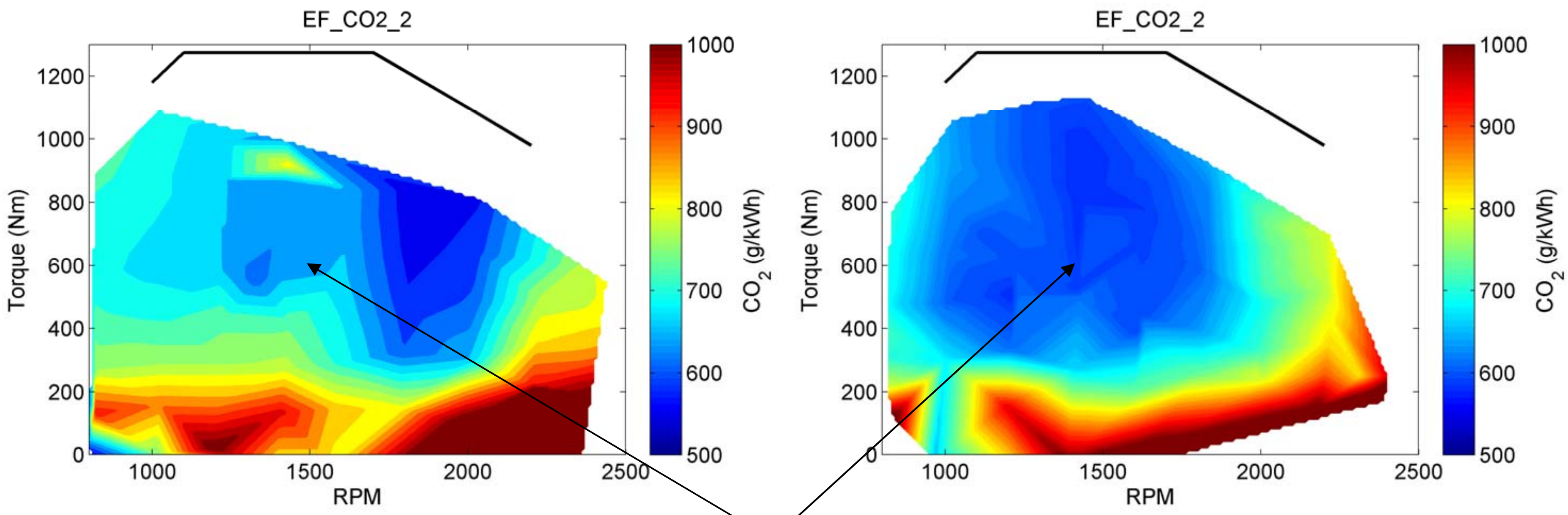
Substitution ratio

$$Energy\ substitution\ ratio = \frac{energy_{natgas}}{energy_{natgas} + energy_{diesel}}$$



CO_2 emissions

Diesel | Dual-fuel

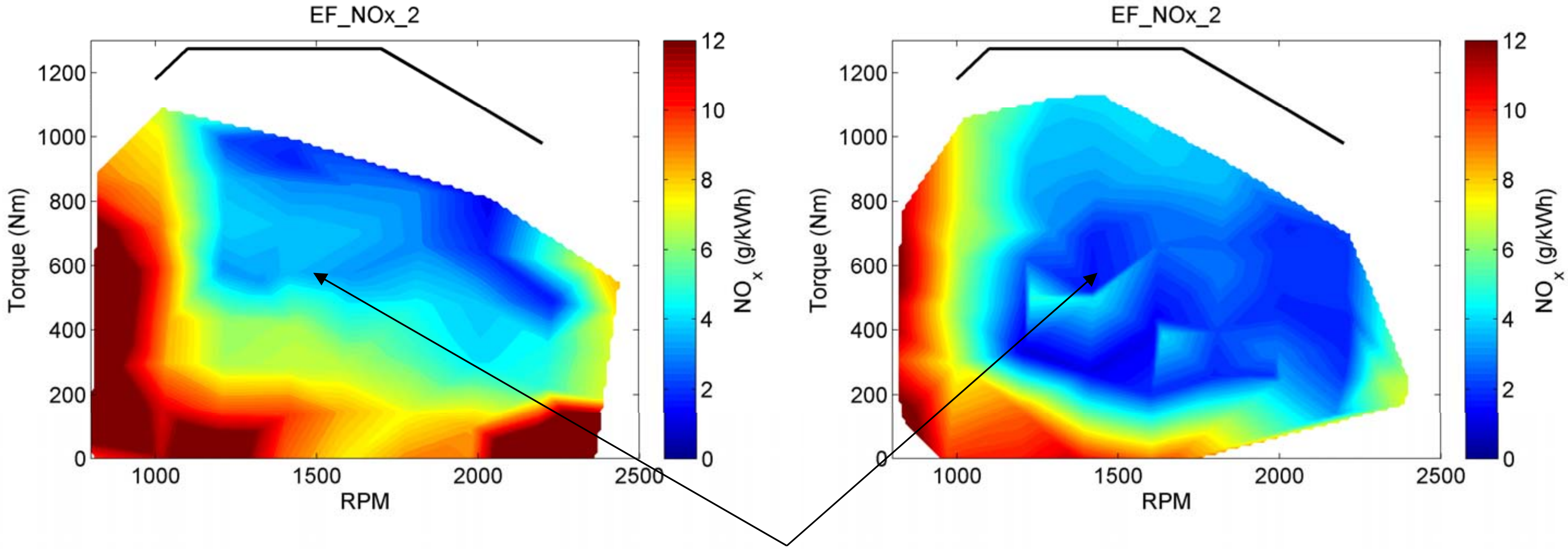


-10% CO_2 @ 1500 rpm, 600 Nm

C:H ratio + 50% natural gas → -12% CO_2

Tailpipe NOx

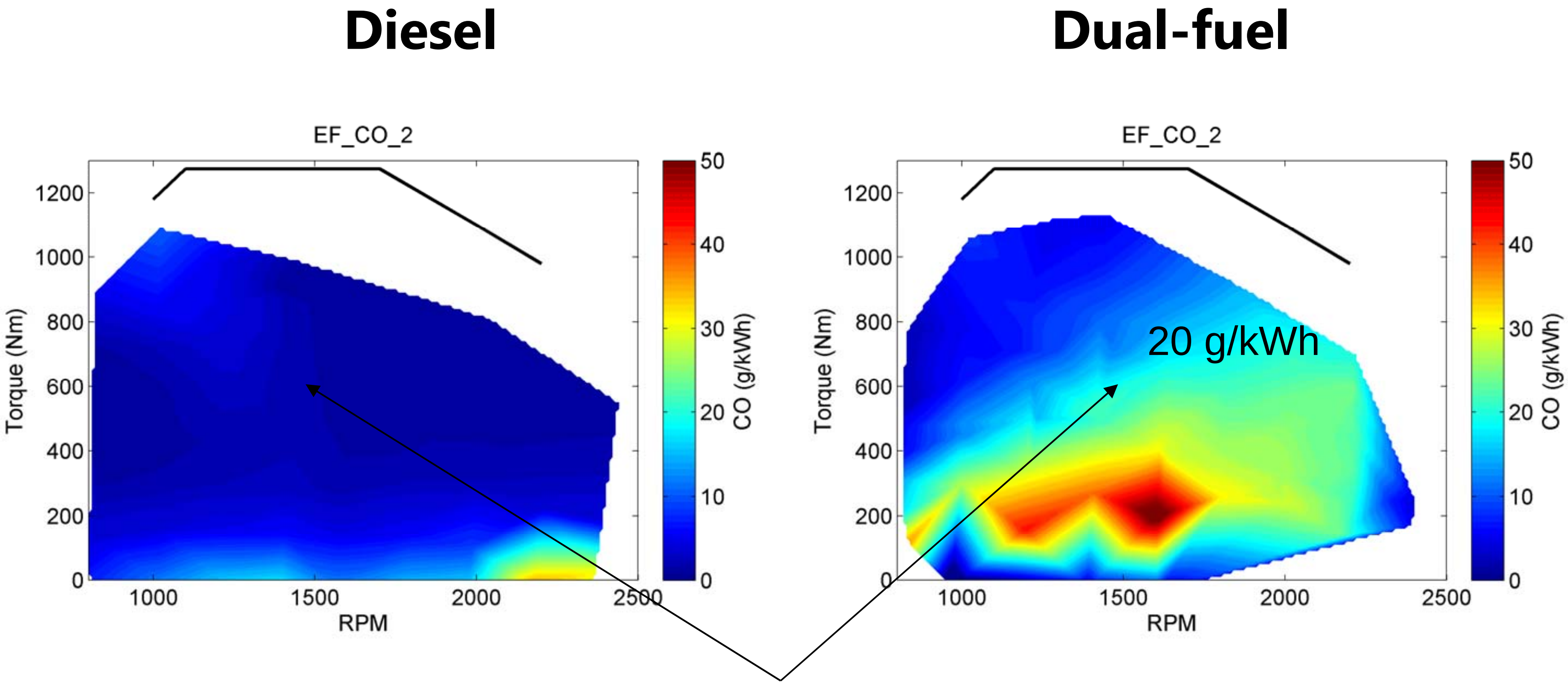
Diesel **Dual-fuel**



-44% NOx @ 1500 rpm, 600 Nm

EURO V limit: 2.0 g/kWh (ESC)

Tailpipe CO

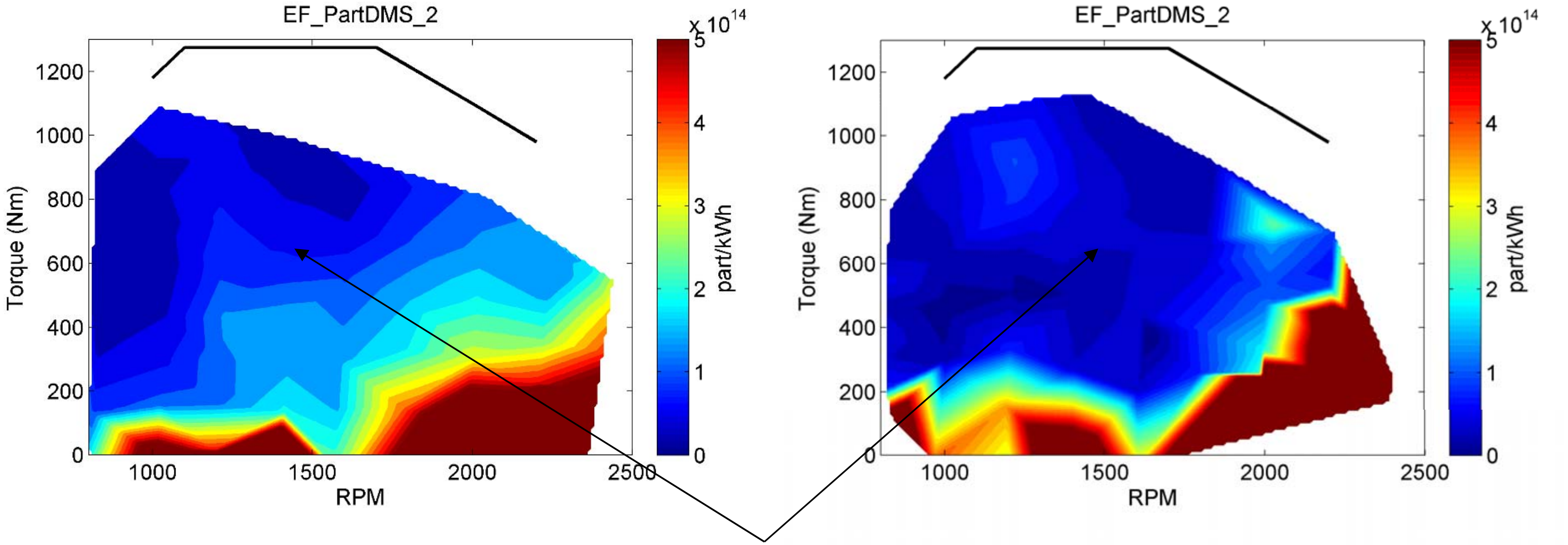


x10 CO @ 1500 rpm, 600 Nm

EURO V limit: 1.5 g/kWh

Particle number emissions

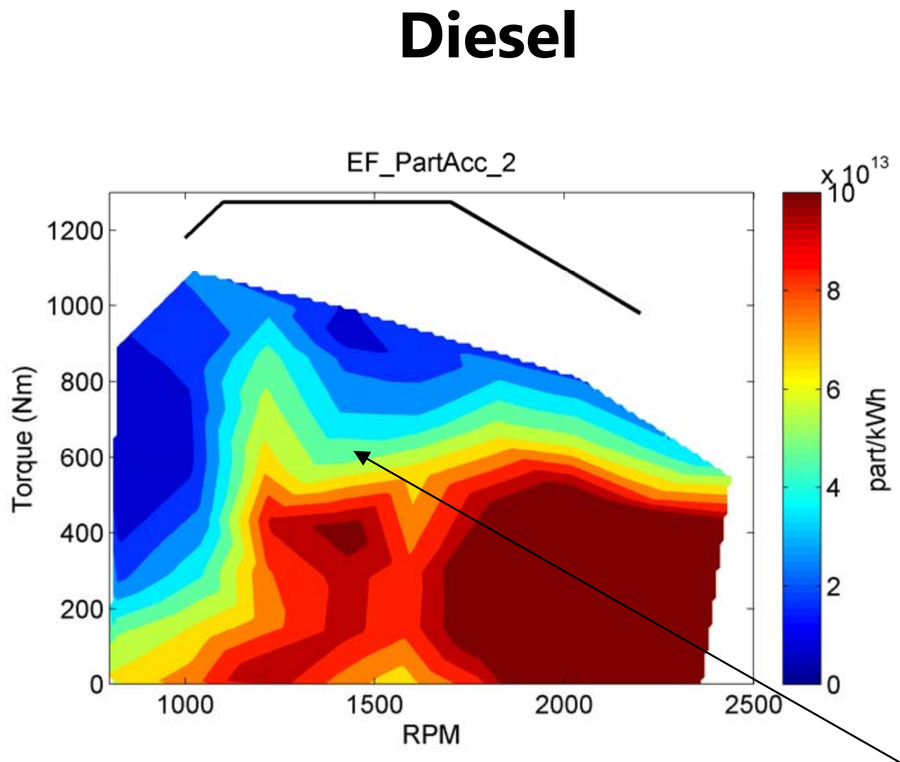
Diesel | **Dual-fuel**

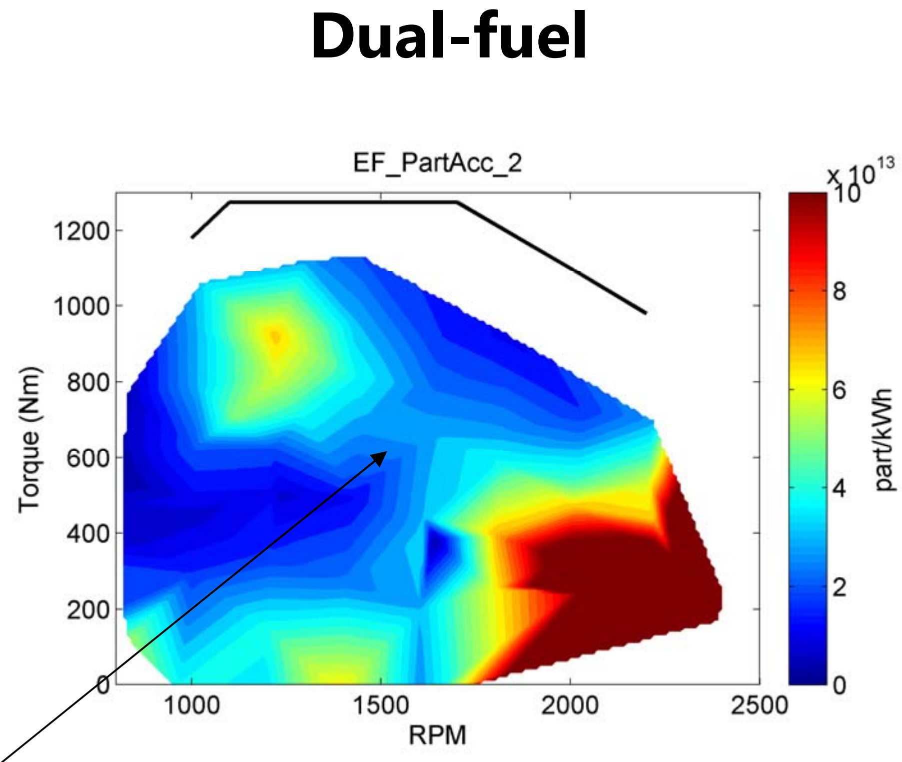


-60% particle number @ 1500 rpm, 600 Nm

DMS500 (5-1000 nm)

Accumulation mode PN





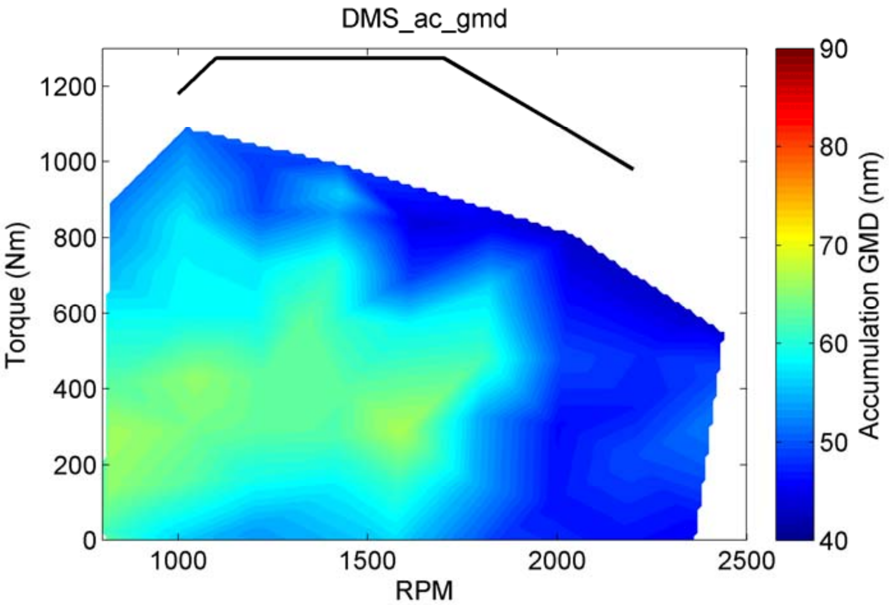
-50% Accumulation mode PN @ 1500 rpm, 600 Nm

DMS500

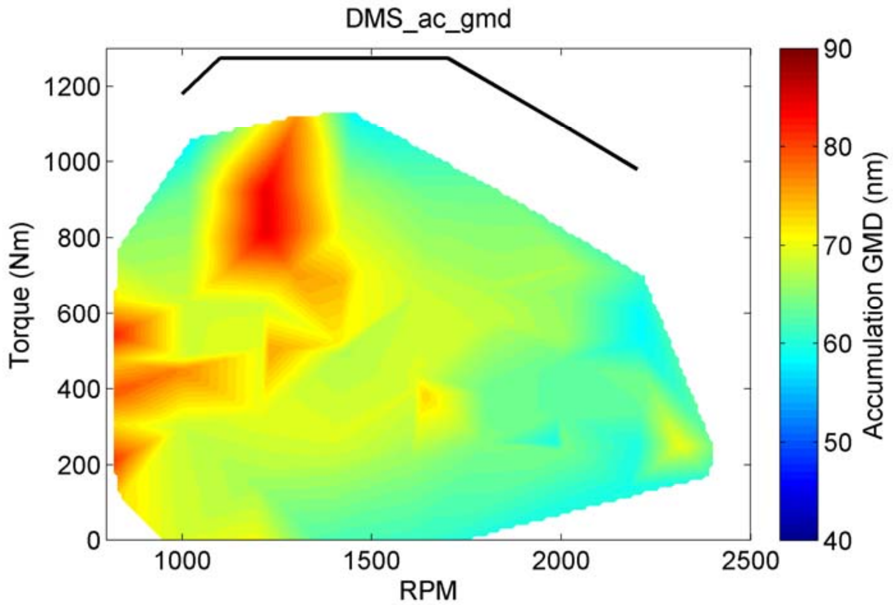
[EURO VI limit 8×10^{11} part/kWh (>23 nm)]

Accumulation GMD

Diesel



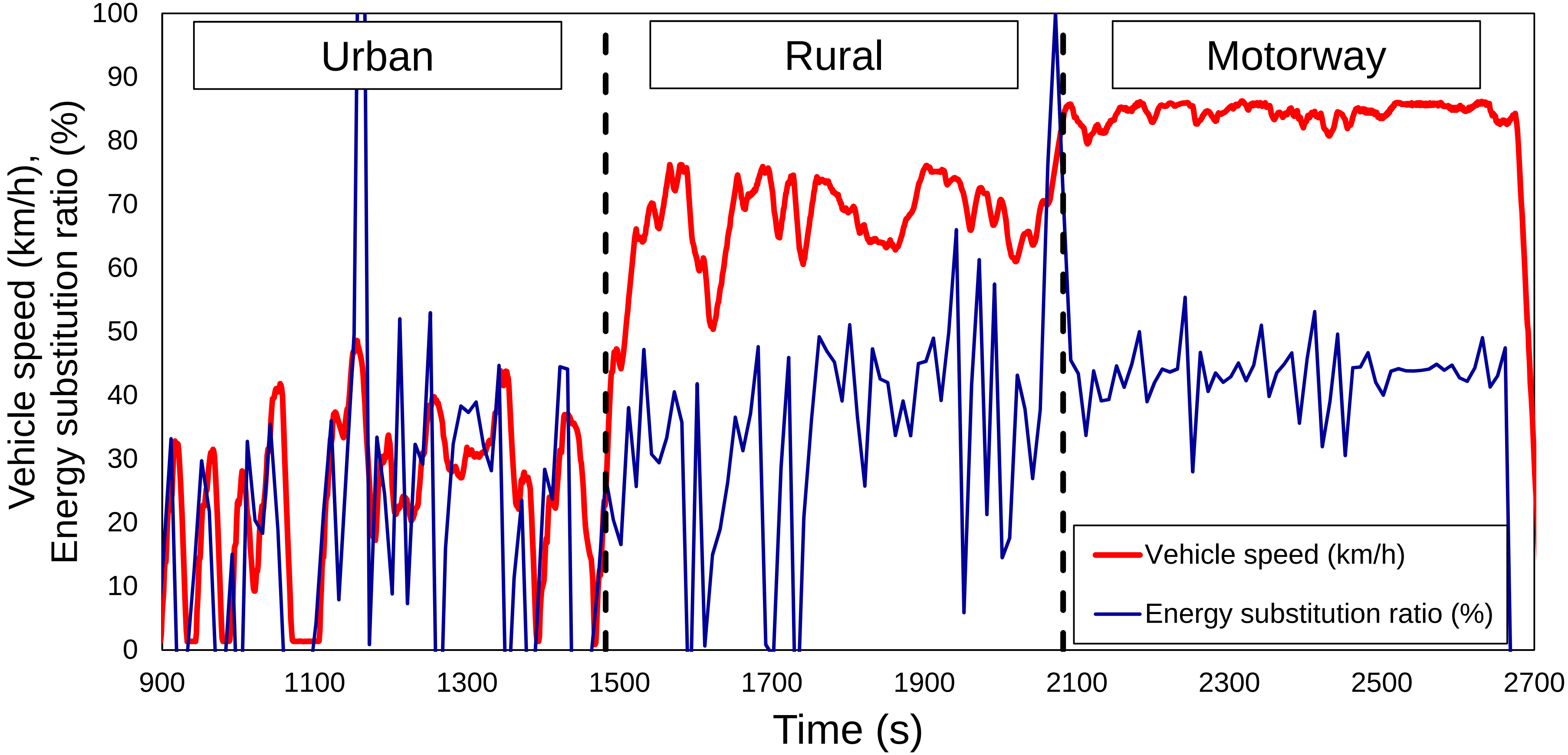
Dual-fuel



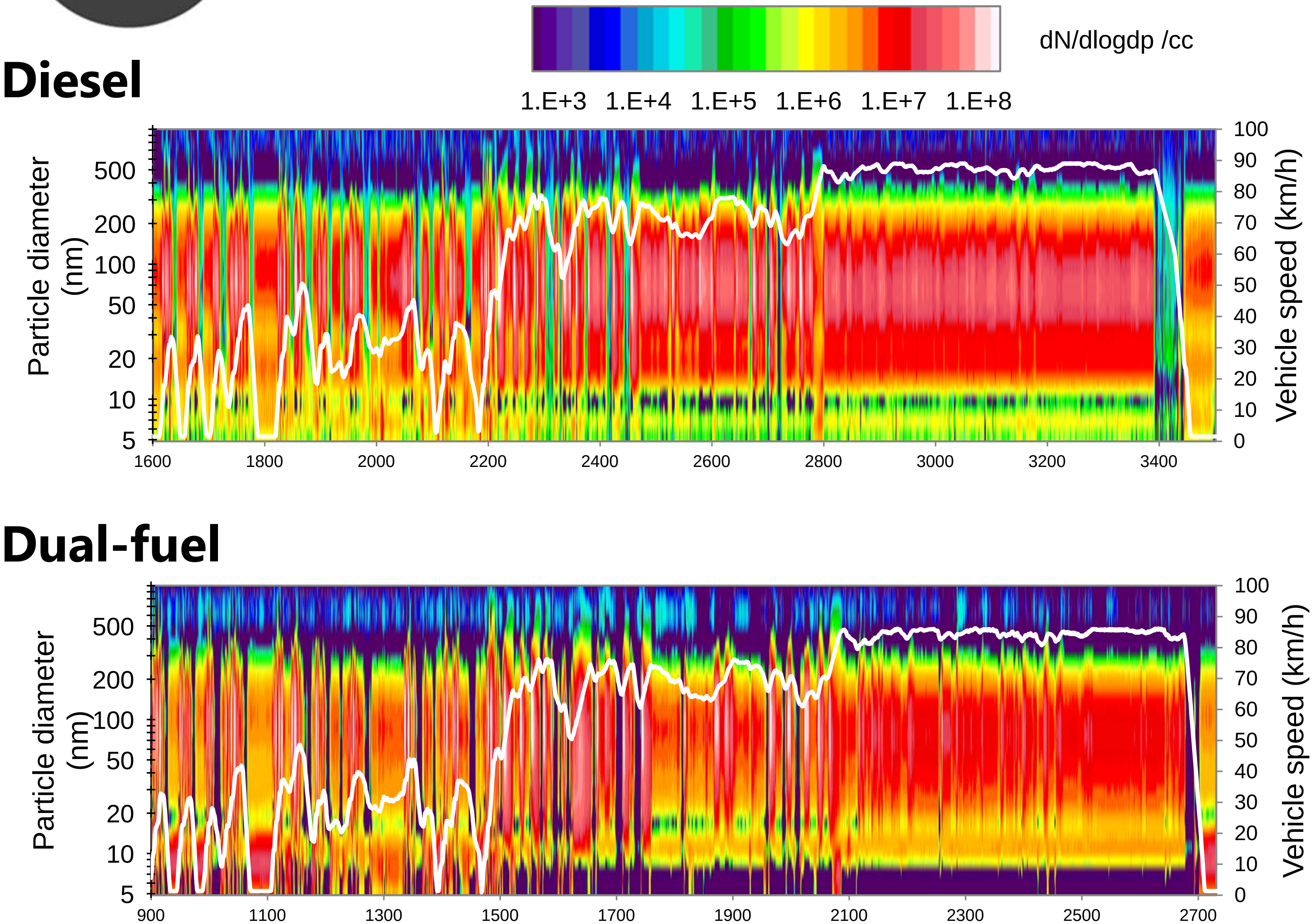
Significant increase in accumulation mode GMD
after dual-fuel conversion
55-70 nm → 65-85 nm

Transient cycle

- European transient cycle (ETC, or FIGE)



Transient cycle (ETC) comparison



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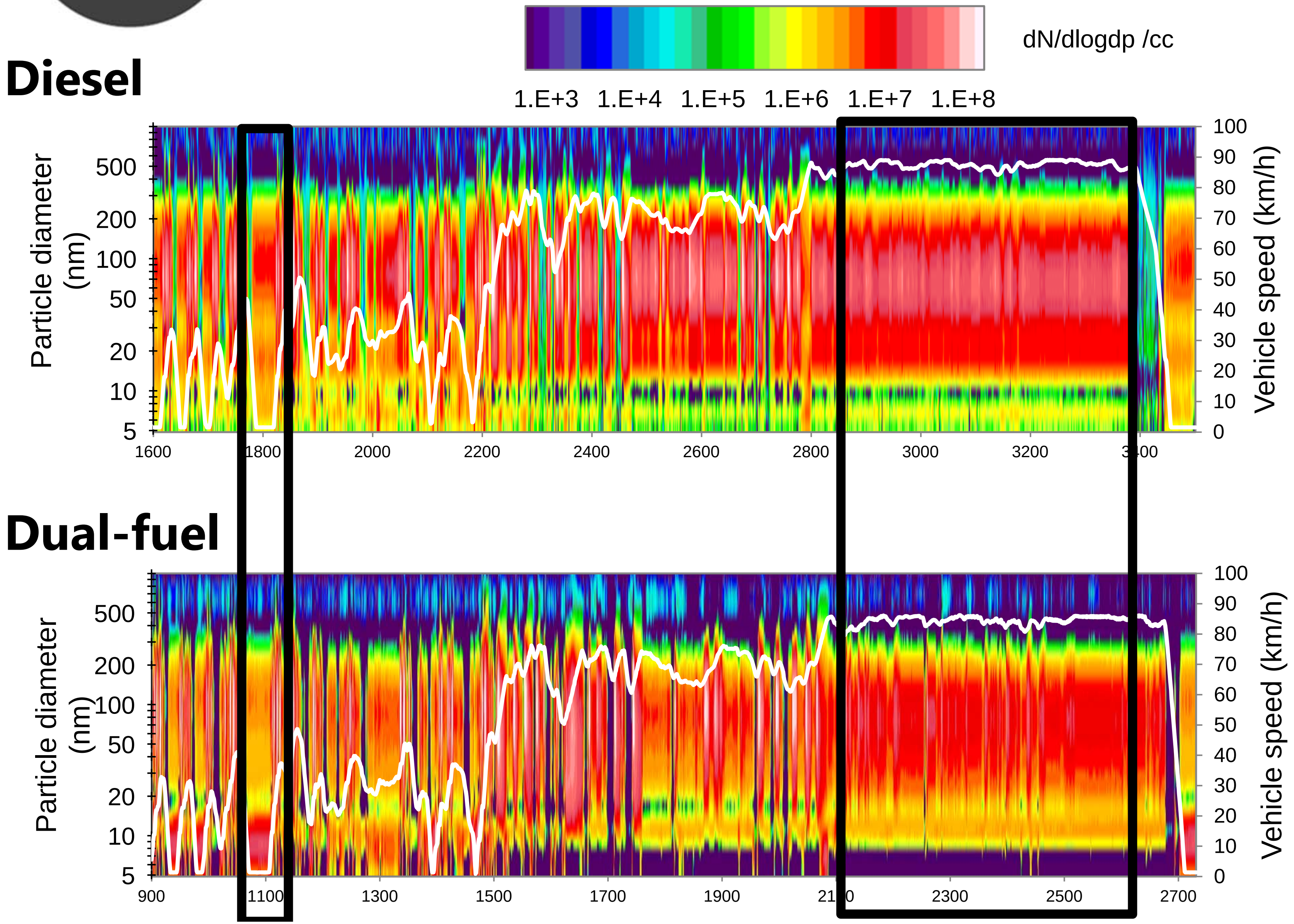

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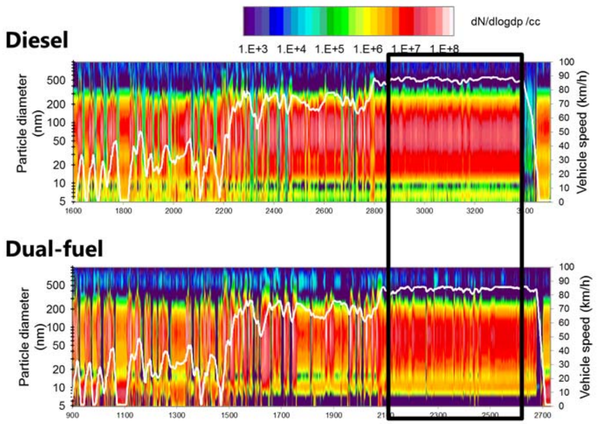

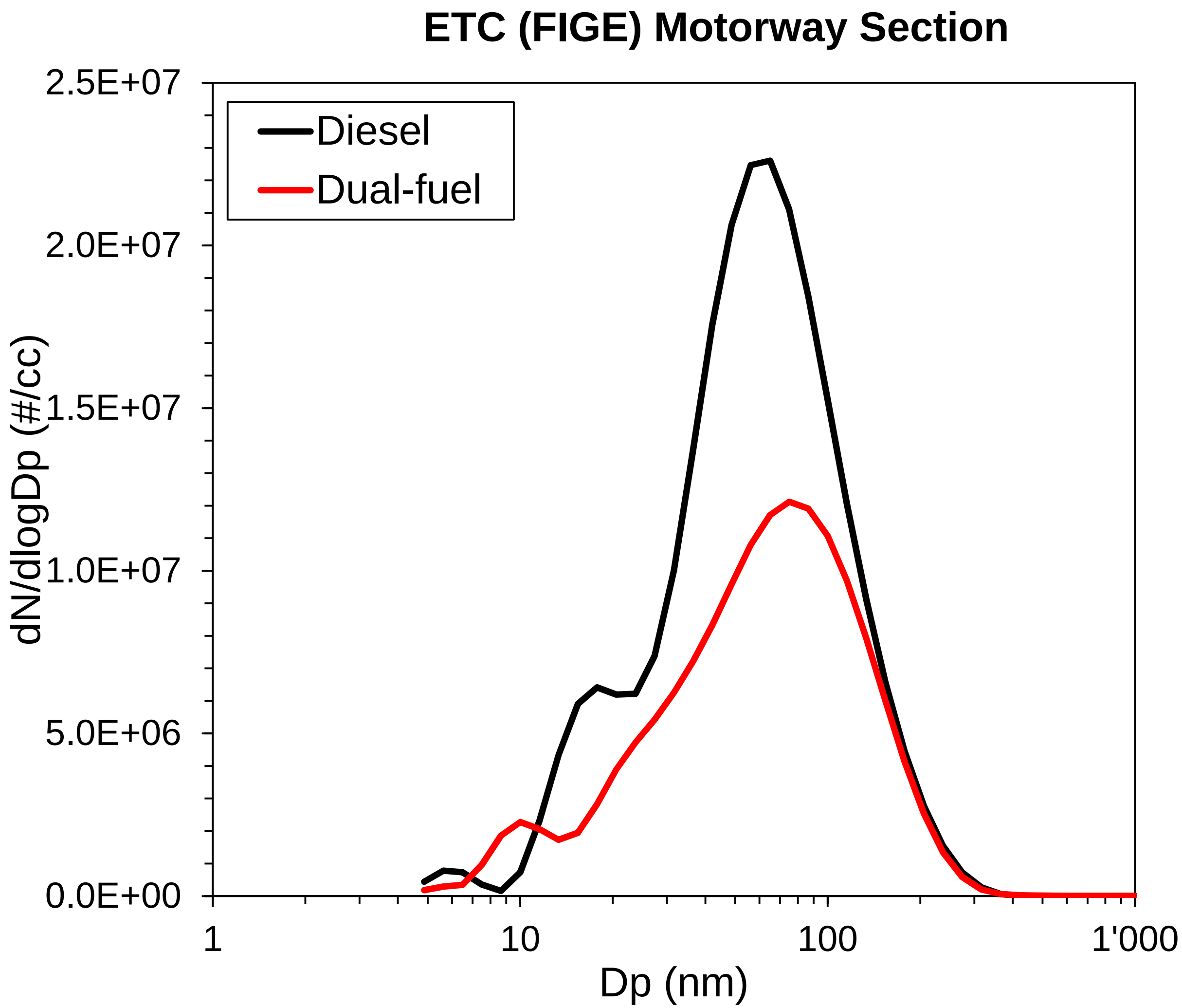

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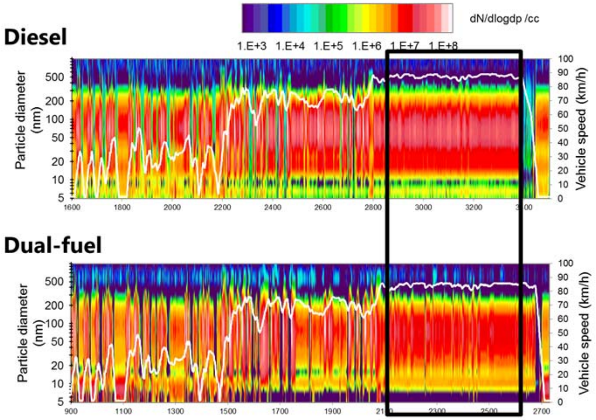
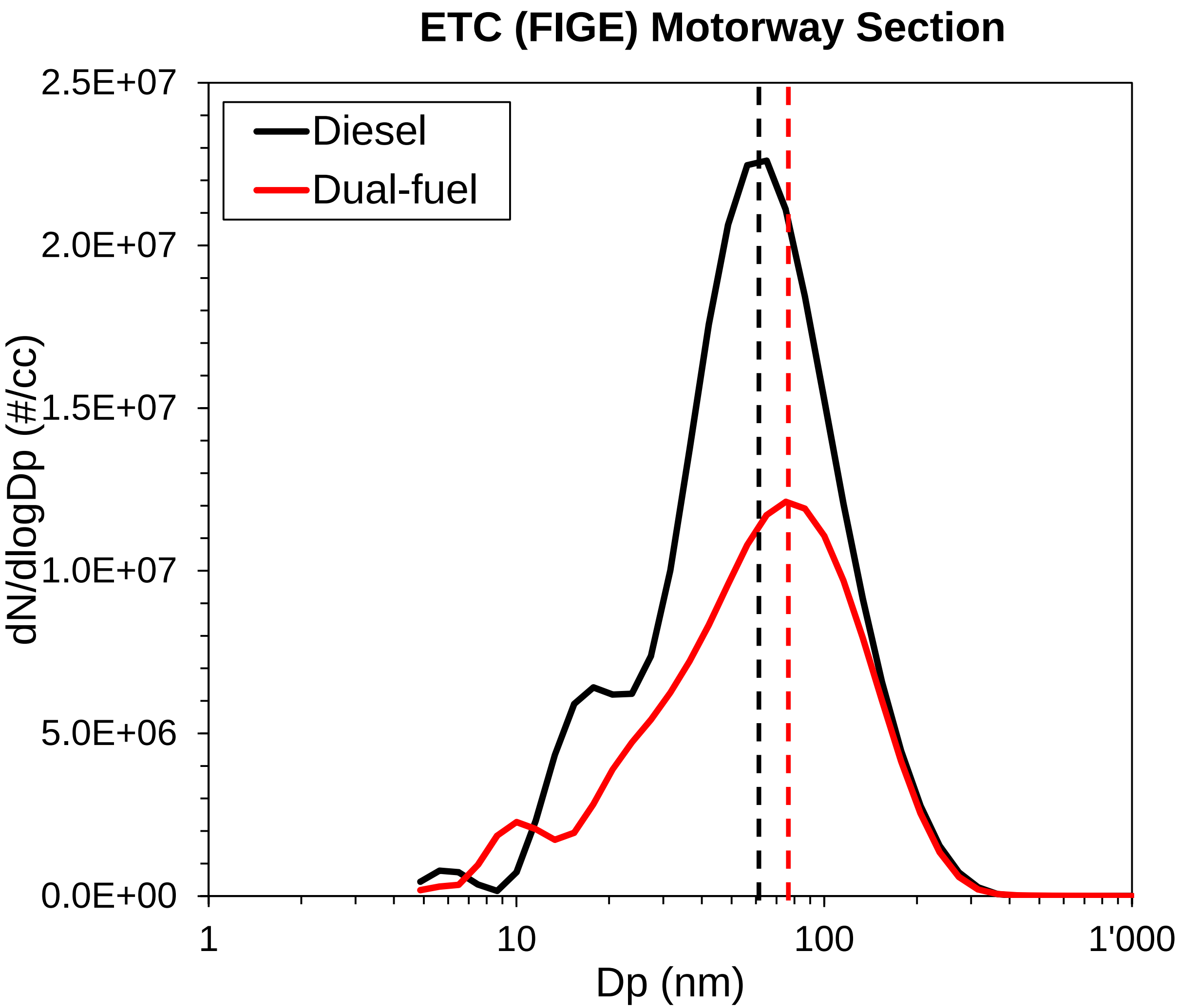


- Accumulation mode GMD increased from 65 nm to 75 nm



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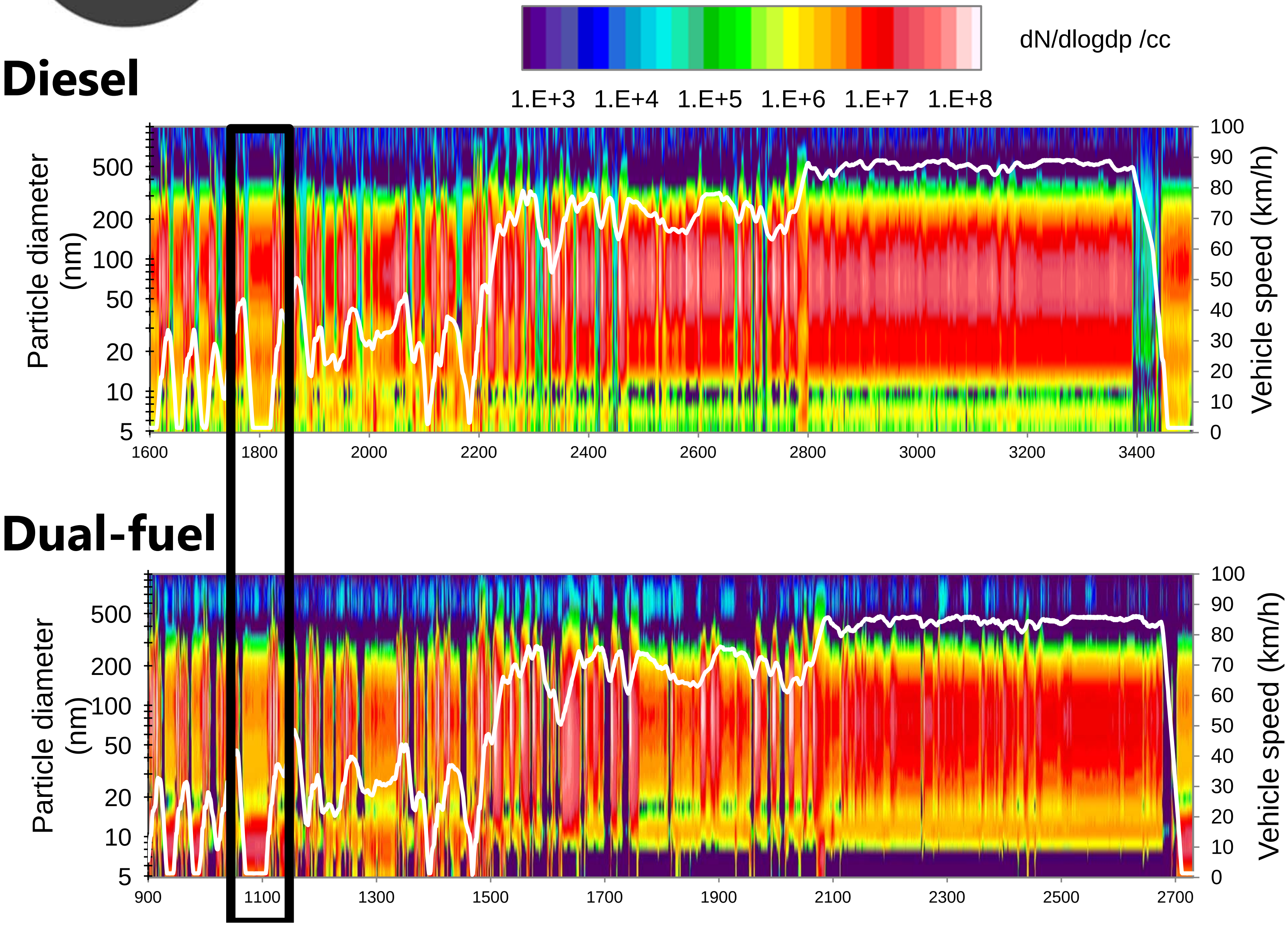

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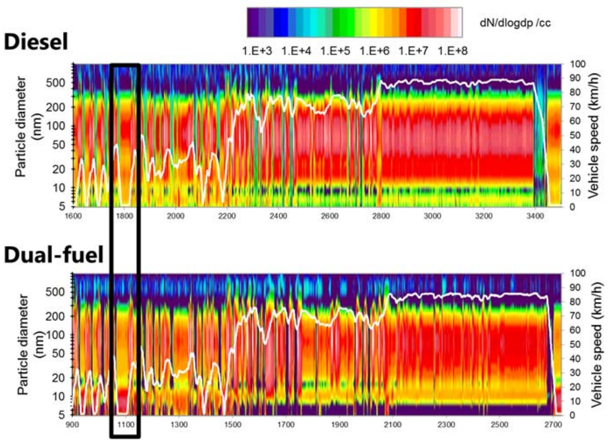
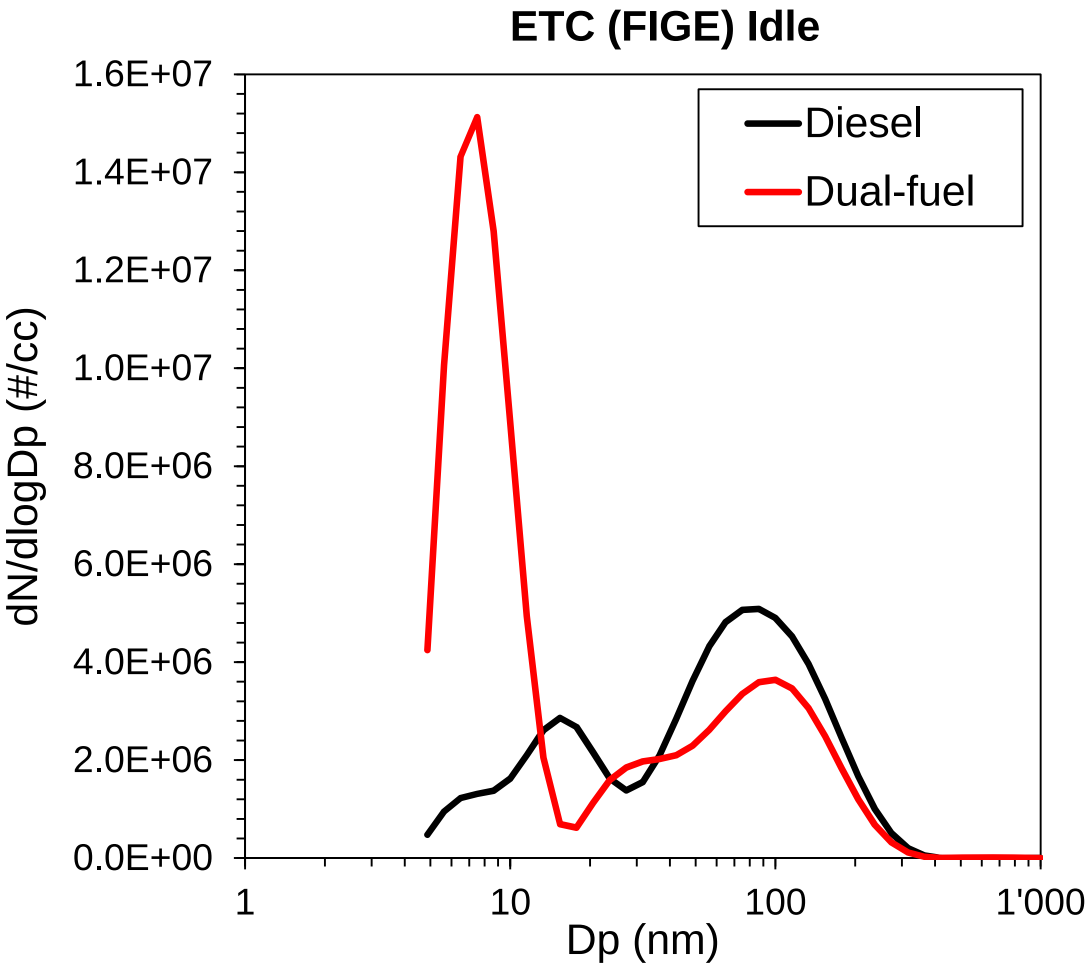


- No gas at Idle
- Dual-fuel conversion leads to more nucleation mode particles at Idle



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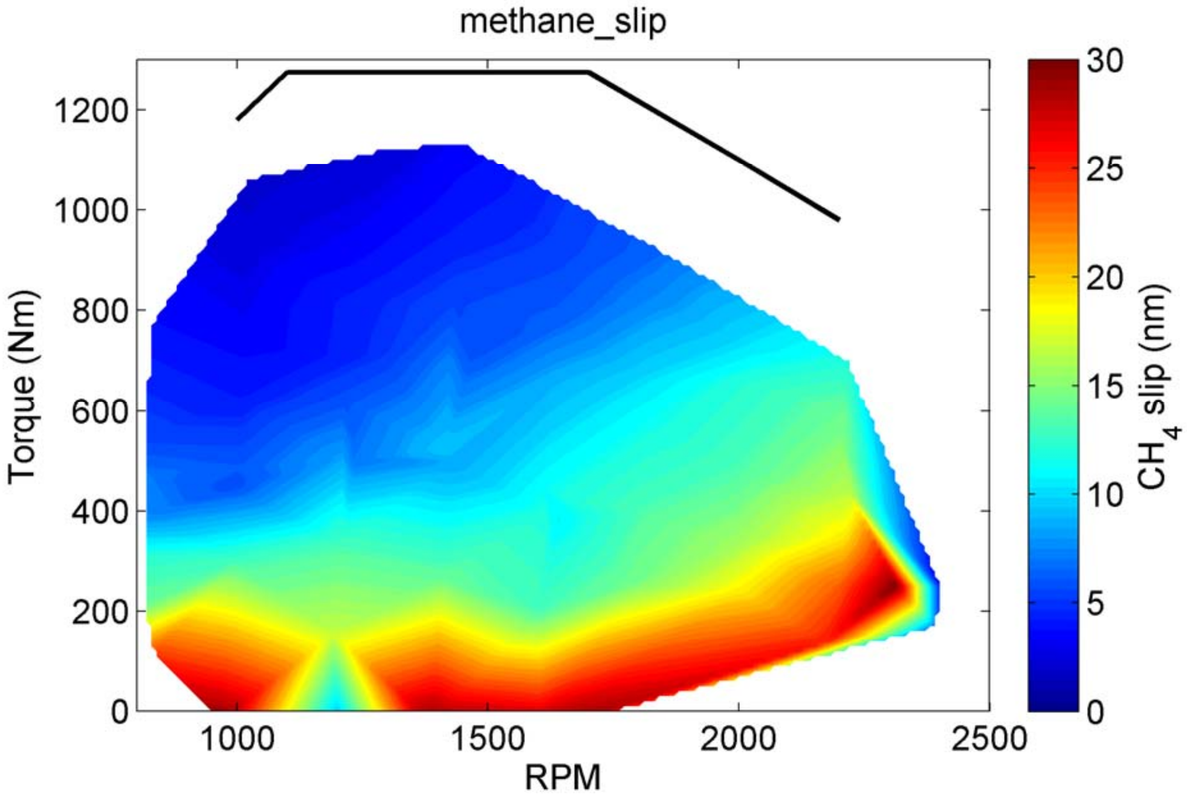
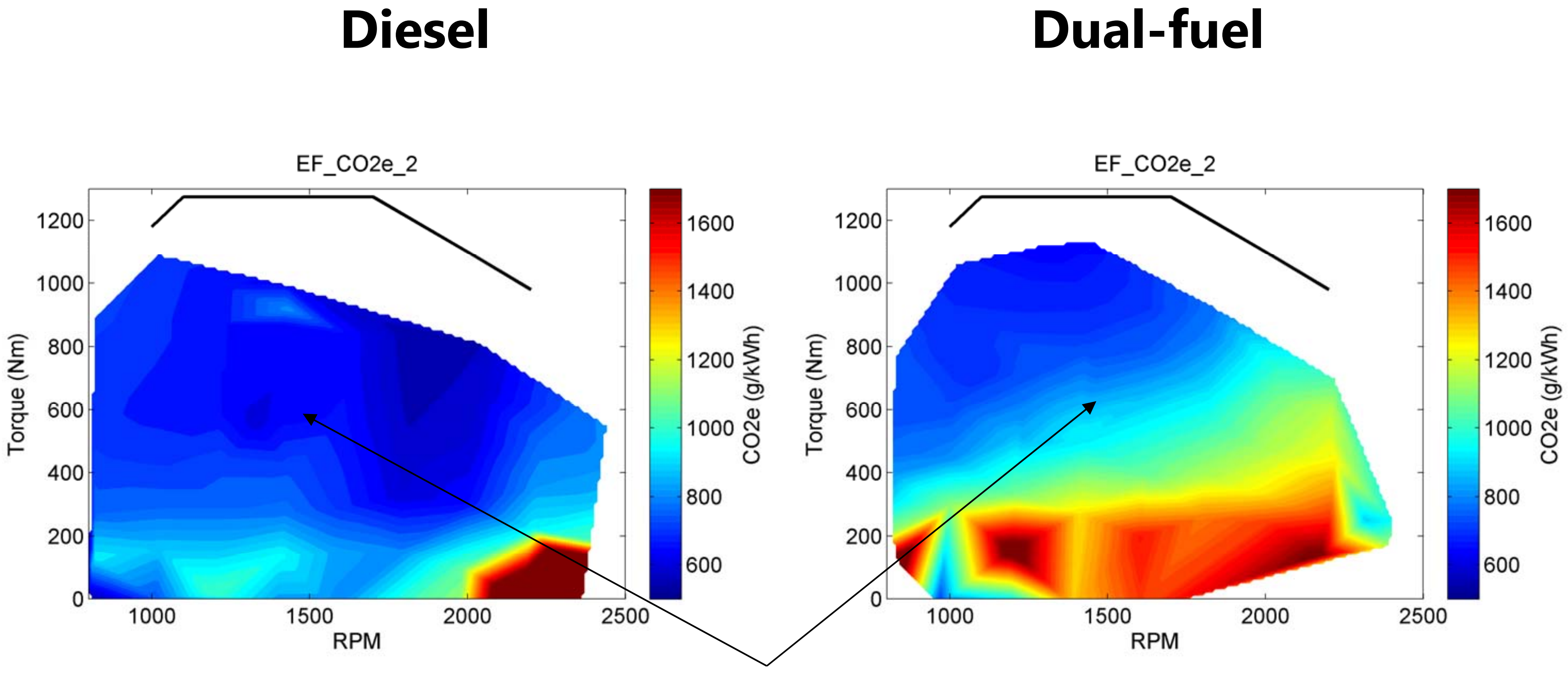
Methane slip



~10% @ 1500 rpm, 600 Nm

Total GHGs - CO_2e



+30% CO2e @ 1500 rpm, 600 Nm

Summary

- Funding for dual-fuel conversions to cut CO_2 in the UK
- Dual-fuel conversion effects on emissions
  - Reduce NOx (~-44%)
  - Increase CO (~x10)
  - Reduce particle number (5-1000 nm, ~-60%)
  - Increase GMD of accumulation mode
  - Increase total GHG (CO2e) by ~30%
  - Effects due to fuel and additions to engine

Further work

- Methane oxidation catalysts
- Crankcase emissions (particles and CH_4)
- Ash particles:

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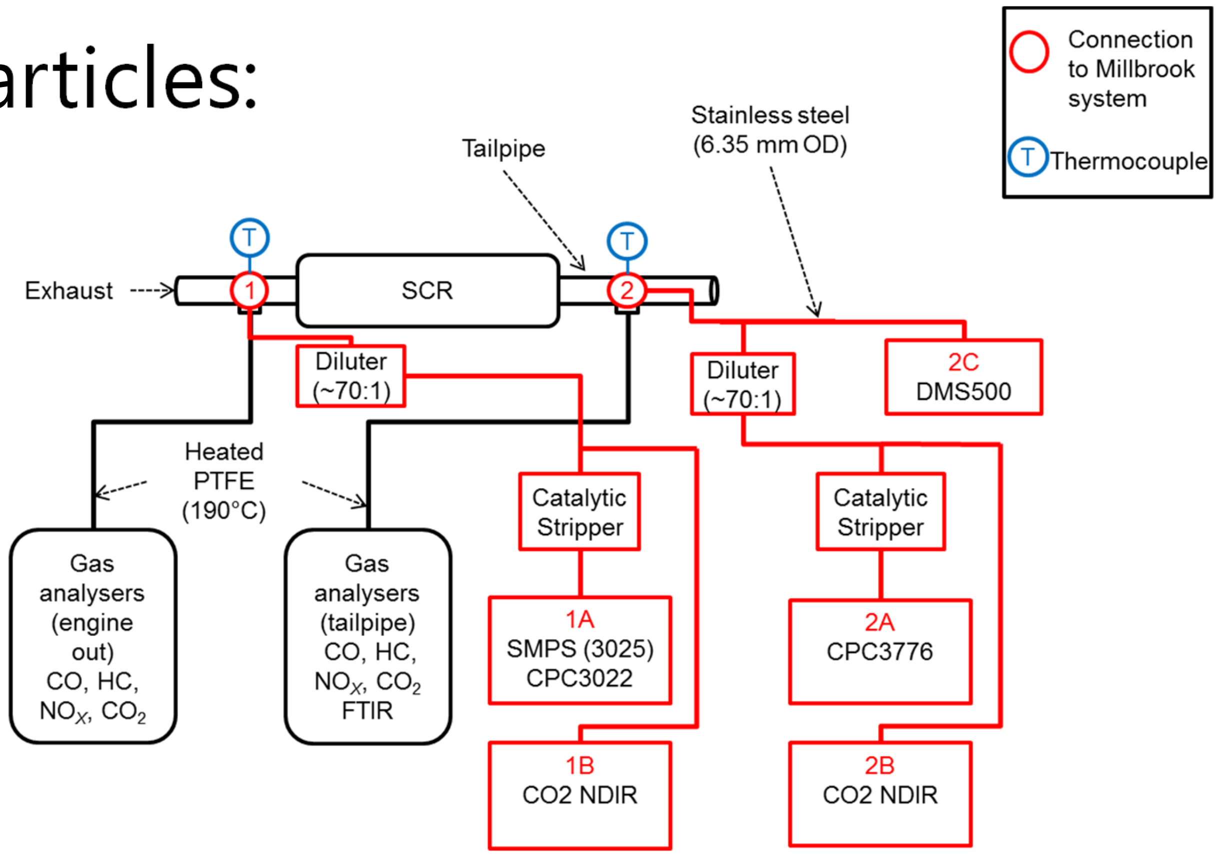
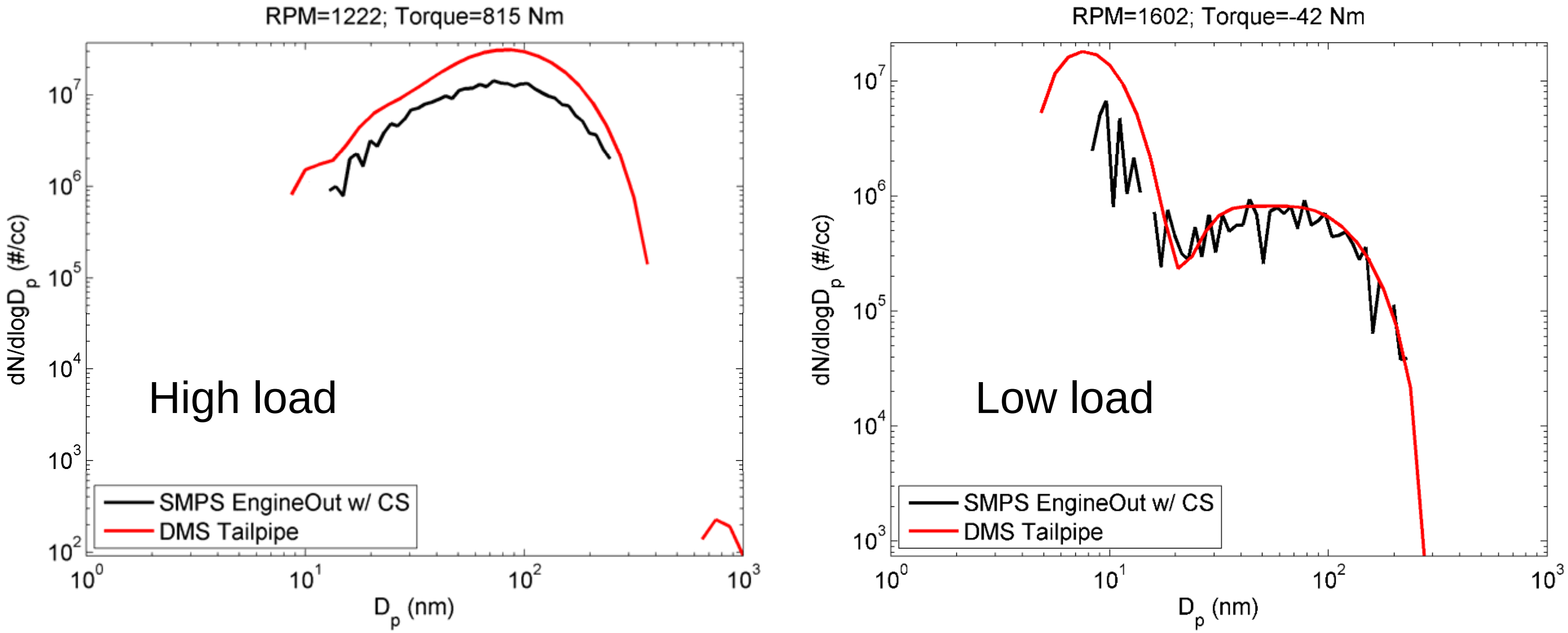
- Ash particles:



Further work

- Methane oxidation catalysts
- Crankcase emissions (particles and CH_4)
- Ash particles:



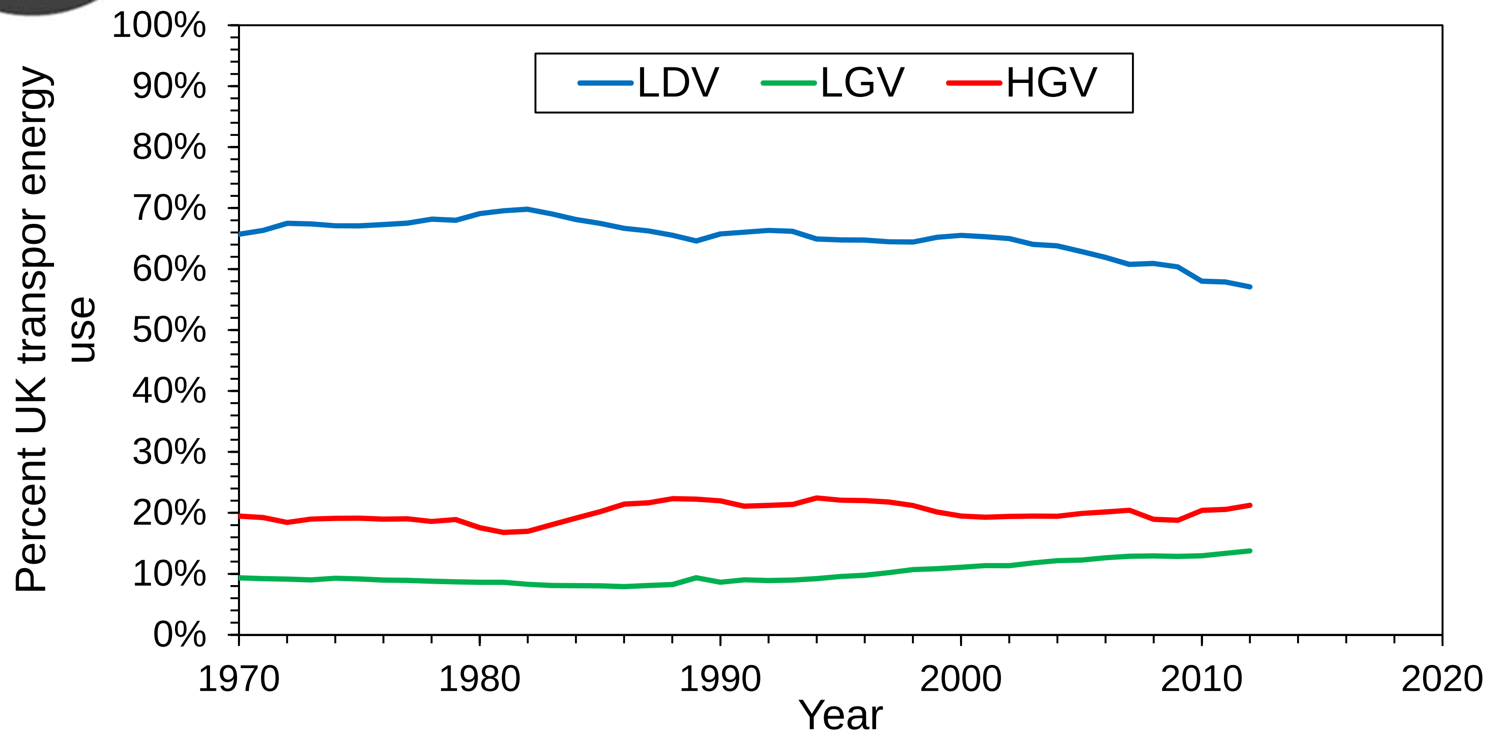
Acknowledgements

- John Lewis Partnership
- Industrial partners
- UK Engineering and Physical Science Research Council (EPSRC)
- Millbrook Proving Ground

Thanks, questions?

ms828@cam.ac.uk

UK transport energy use



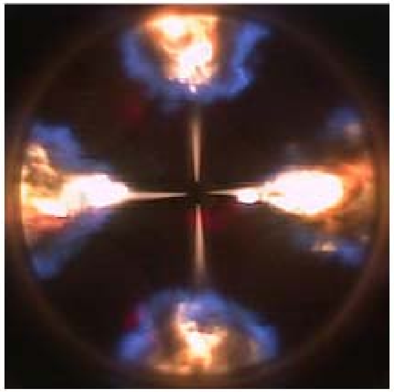
- Freight (HGV) accounts for 21% of transport energy use in UK

Dual-fuel combustion

- Pilot diesel injection provides 'spark'
- Gas 'fumigation'
- CO_2 emissions depend on
  - C:H ratio of fuel
    - **Diesel: $\approx C_{12}H_{22}$, i.e. 1:1.85**
    - **Methane: CH_4, i.e. 1:4 (-24%)**
  - Energy substitution ratio

(B)

2 mg diesel



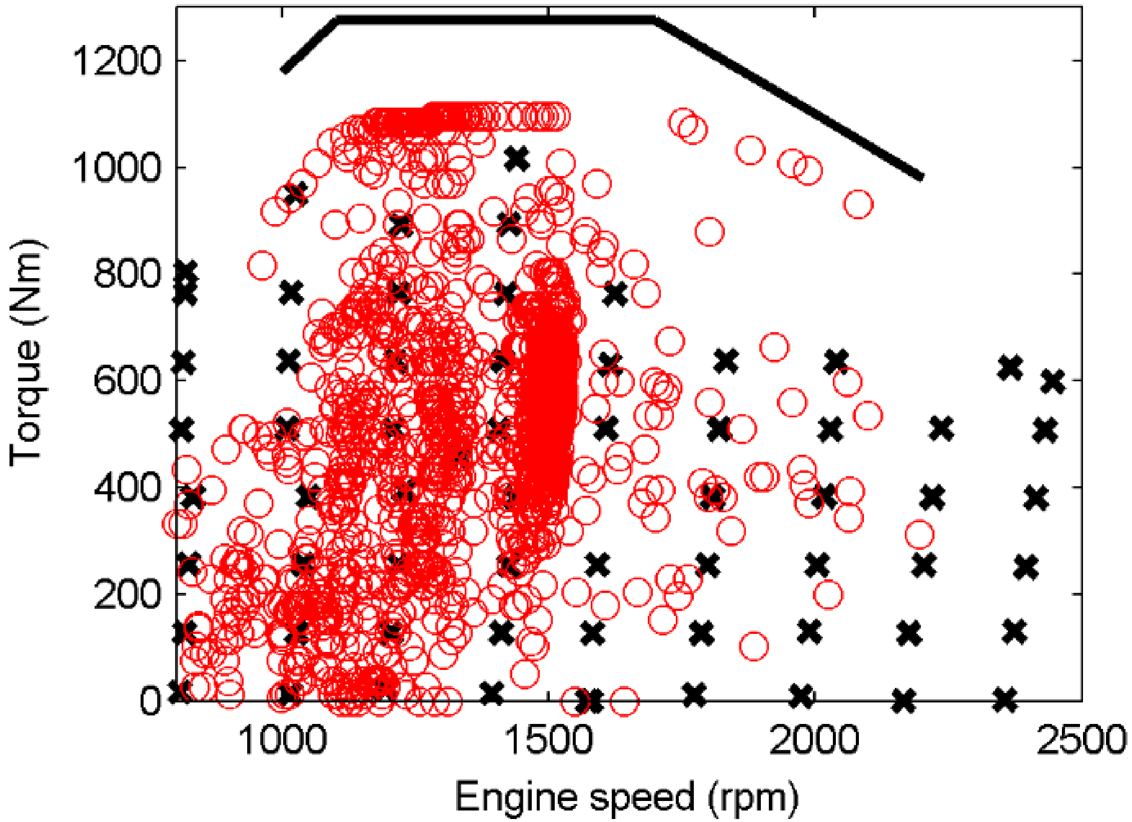
(A)

10 mg diesel

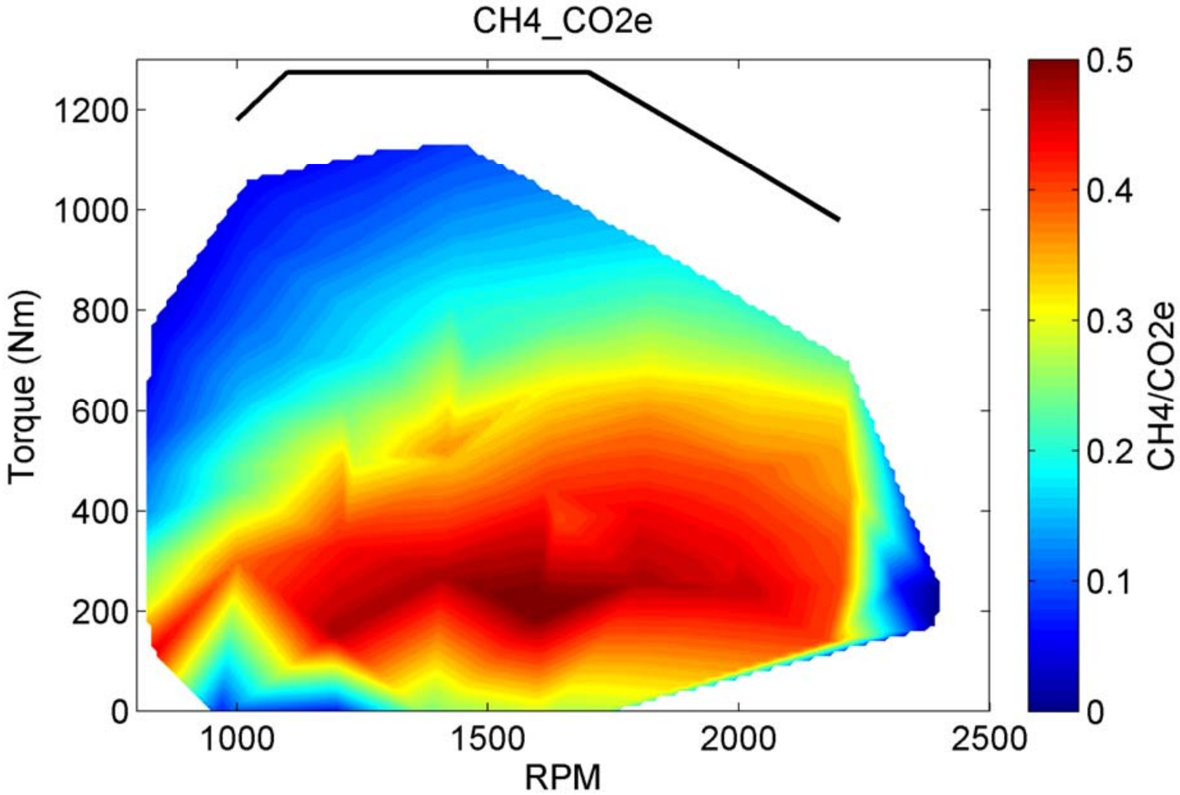
Ulugbek Azimov, E. T. and N. K. (2013). Combustion and Exhaust Emission Characteristics of Diesel Micro-Pilot Ignited Dual-Fuel Engine. In S. Bari (Ed.), *Diesel Engine - Combustion, Emissions and Condition Monitoring*. InTech. doi:10.5772/2782

Test points

- 94% of FIGE transient drive cycle covered by steady-state test points

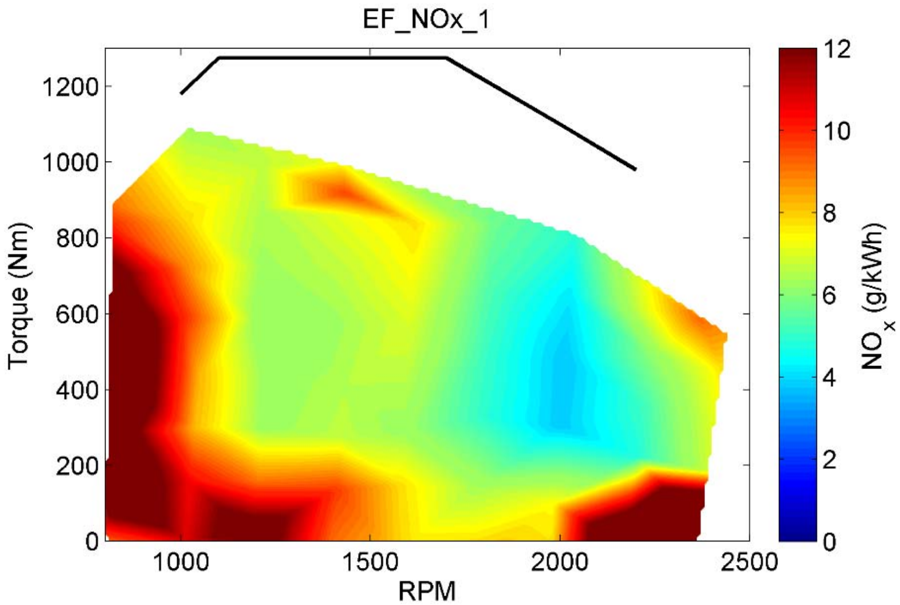


CH_4 contribution to CO_2e

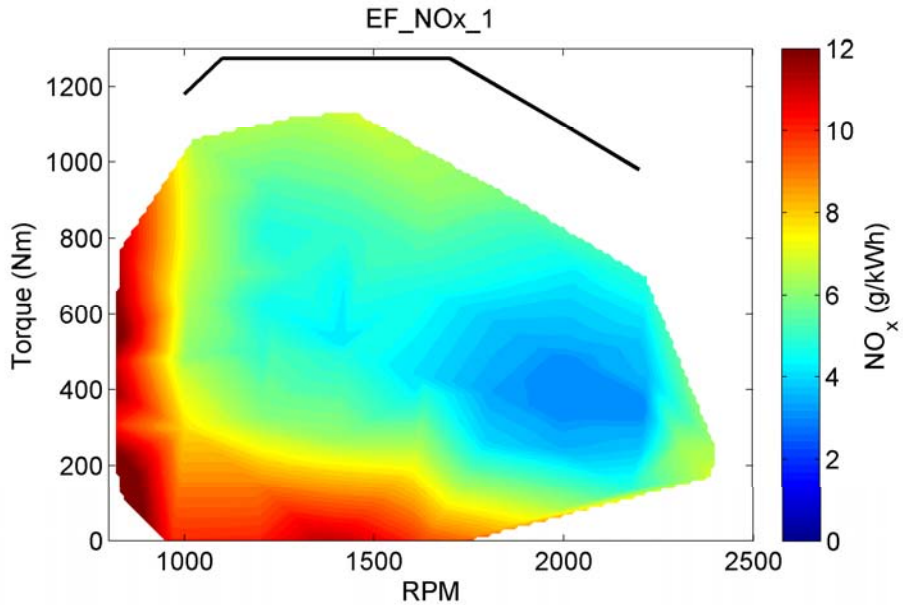


Engine out NOx

Diesel



Dual-fuel

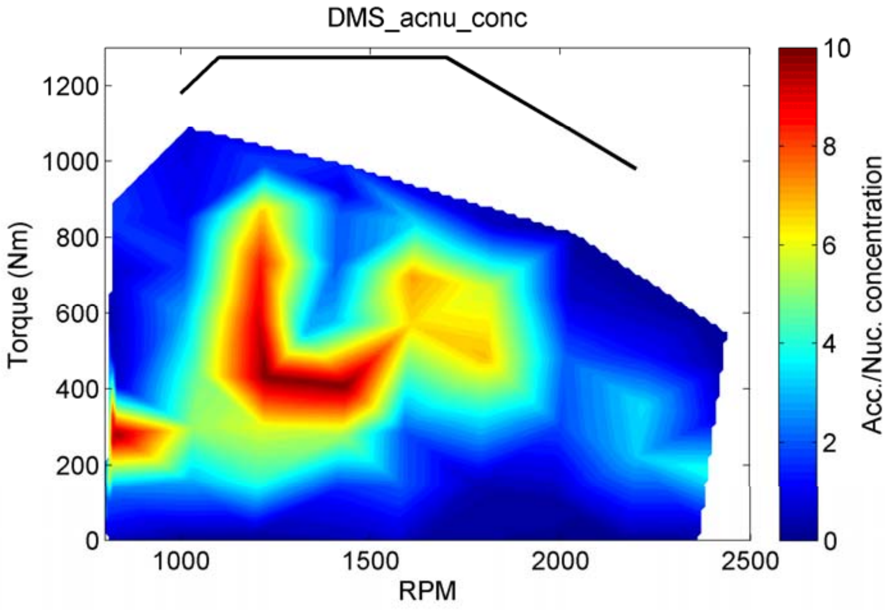


-33% NOx @ 1500 rpm, 600 Nm

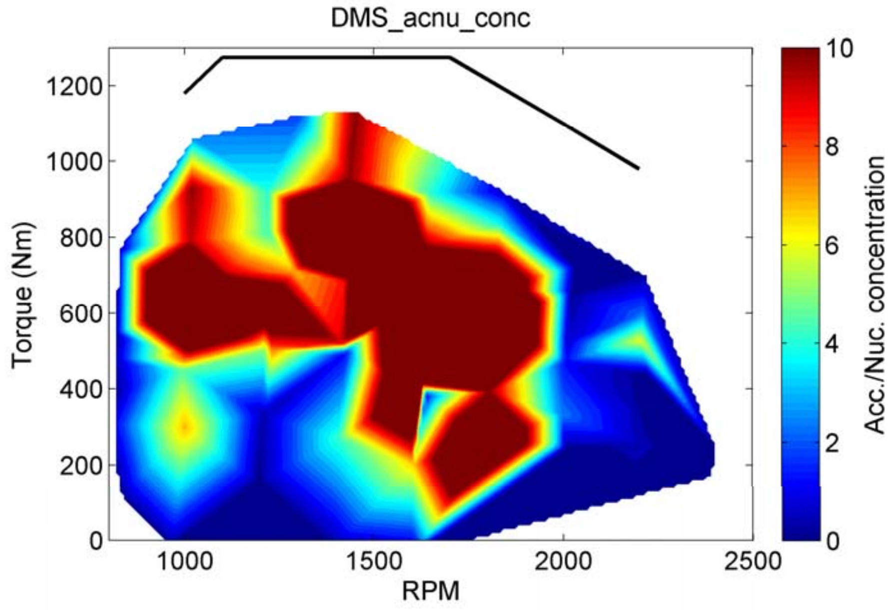
EURO V limit: 2.0 g/kWh

Accumulation/Nucleation

Diesel

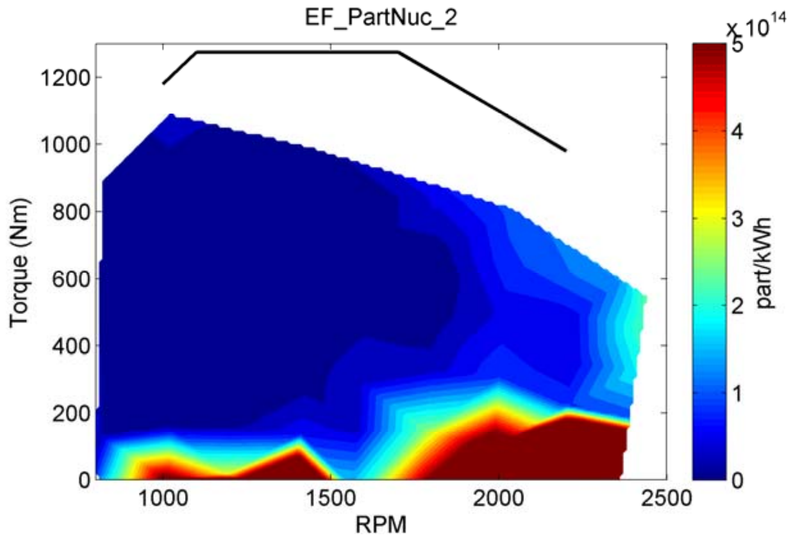


Dual-fuel

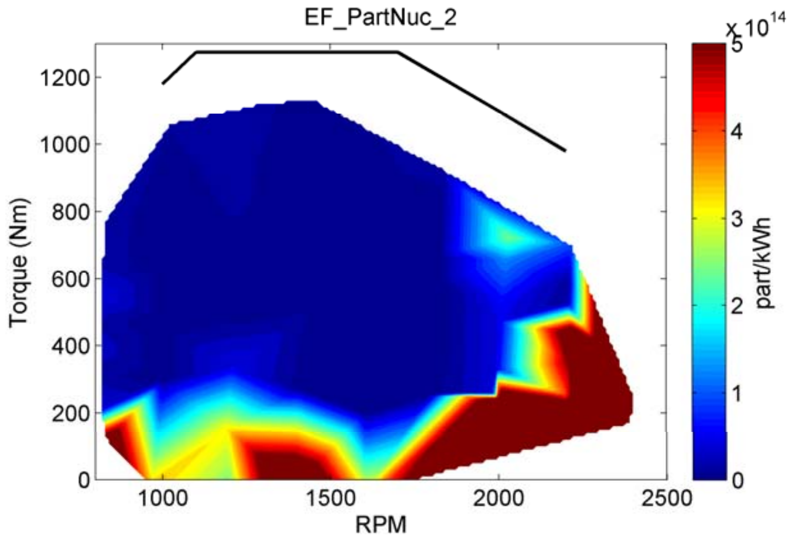


Nucleation mode PM

Diesel

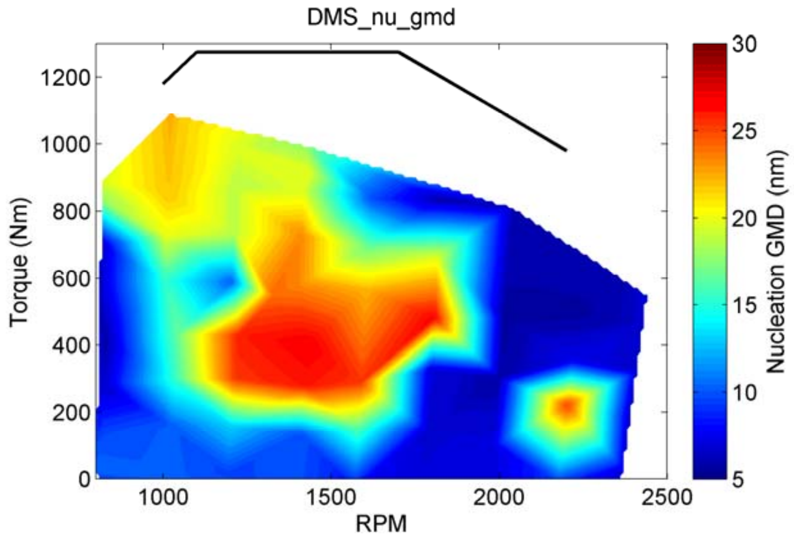


Dual-fuel

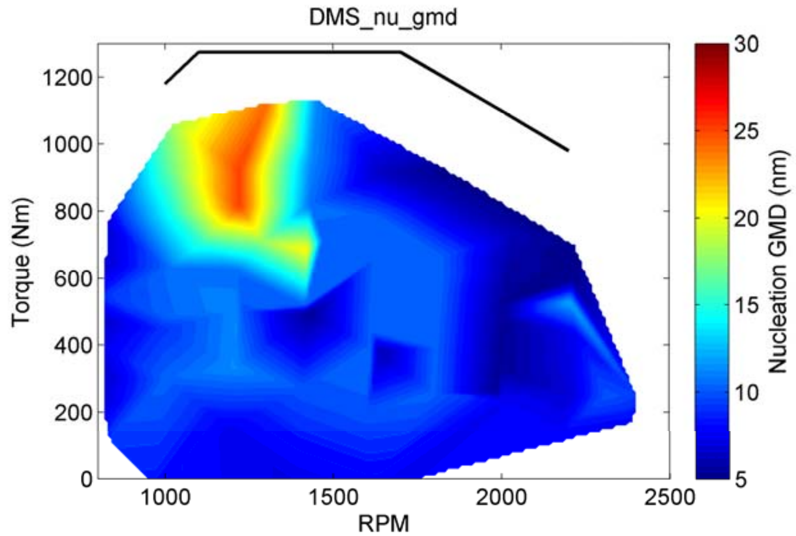


Nucleation GMD

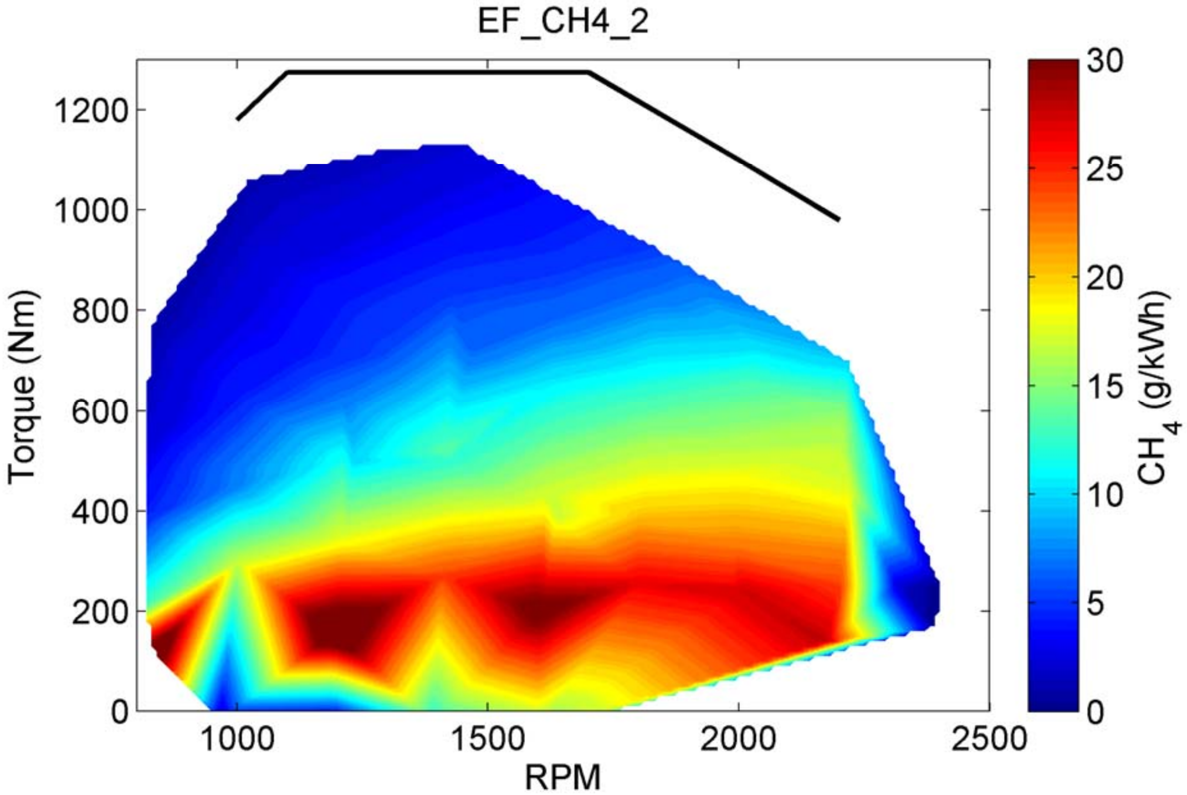
Diesel



Dual-fuel



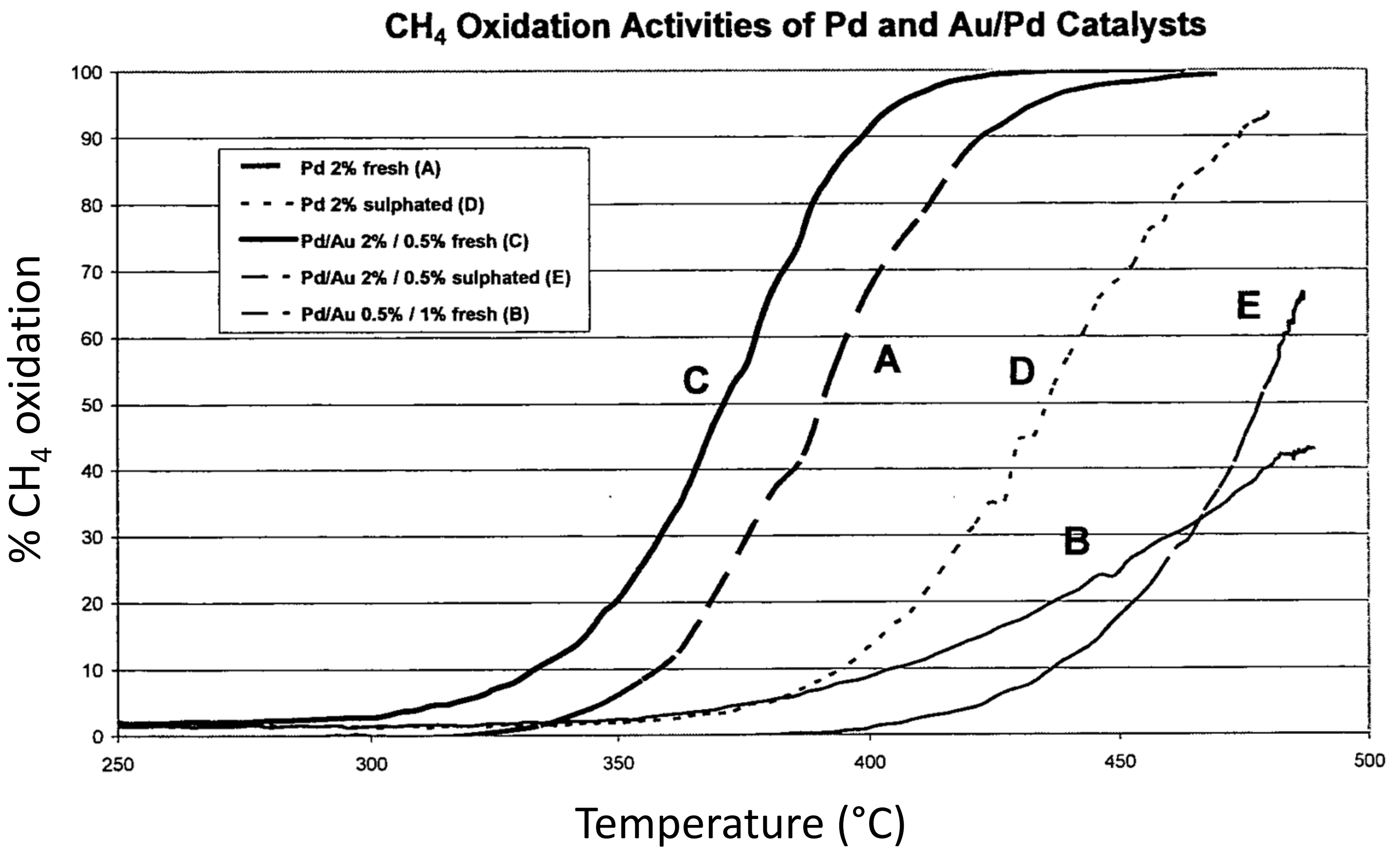
CH_4



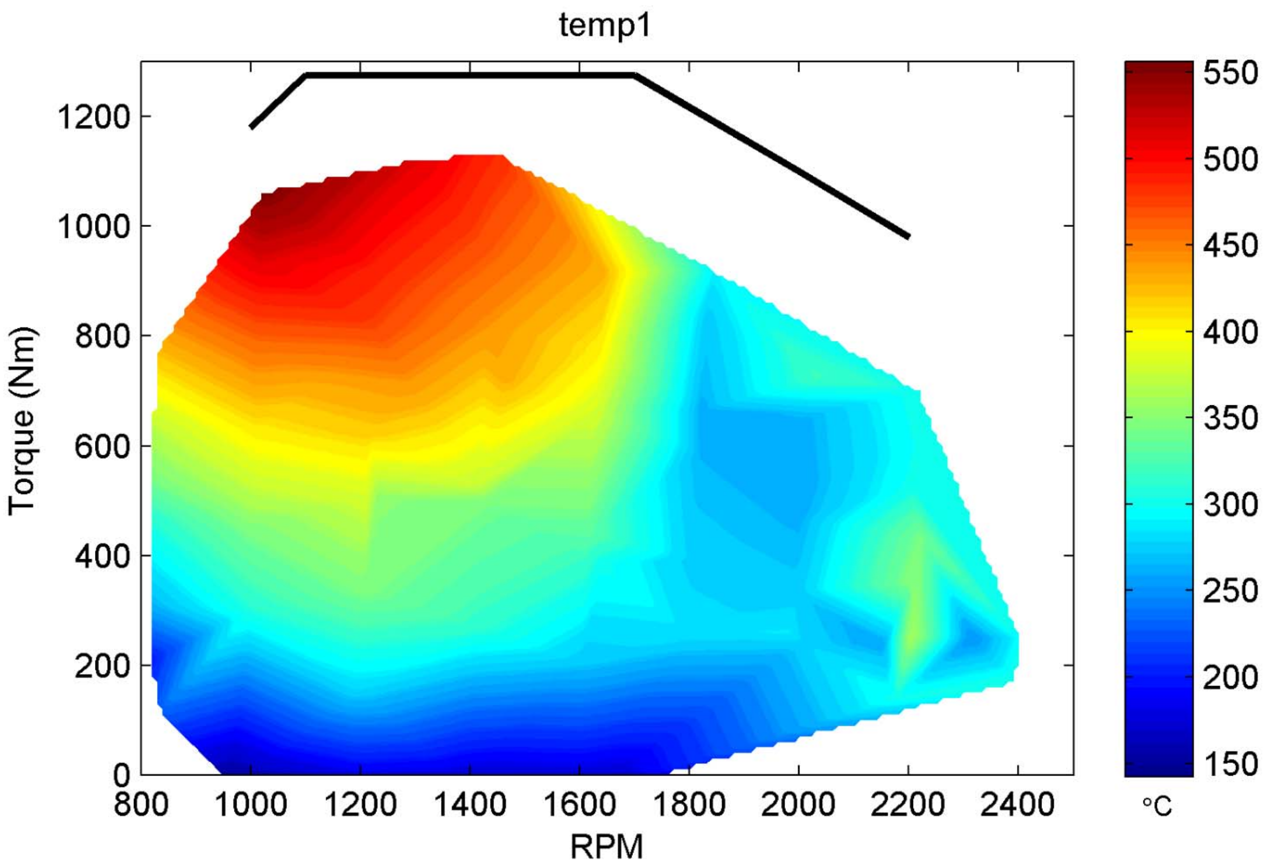
EF_CH4_2
1200
1000
800
600
400
200
0
Torque (Nm)
1000
1500
2000
2500
RPM
30
25
20
15
10
5
0
CH_4 (g/kWh)

Oxidation catalyst activity

- Johnson Matthey
  - Patent No. W02009106849



Exhaust temperatures



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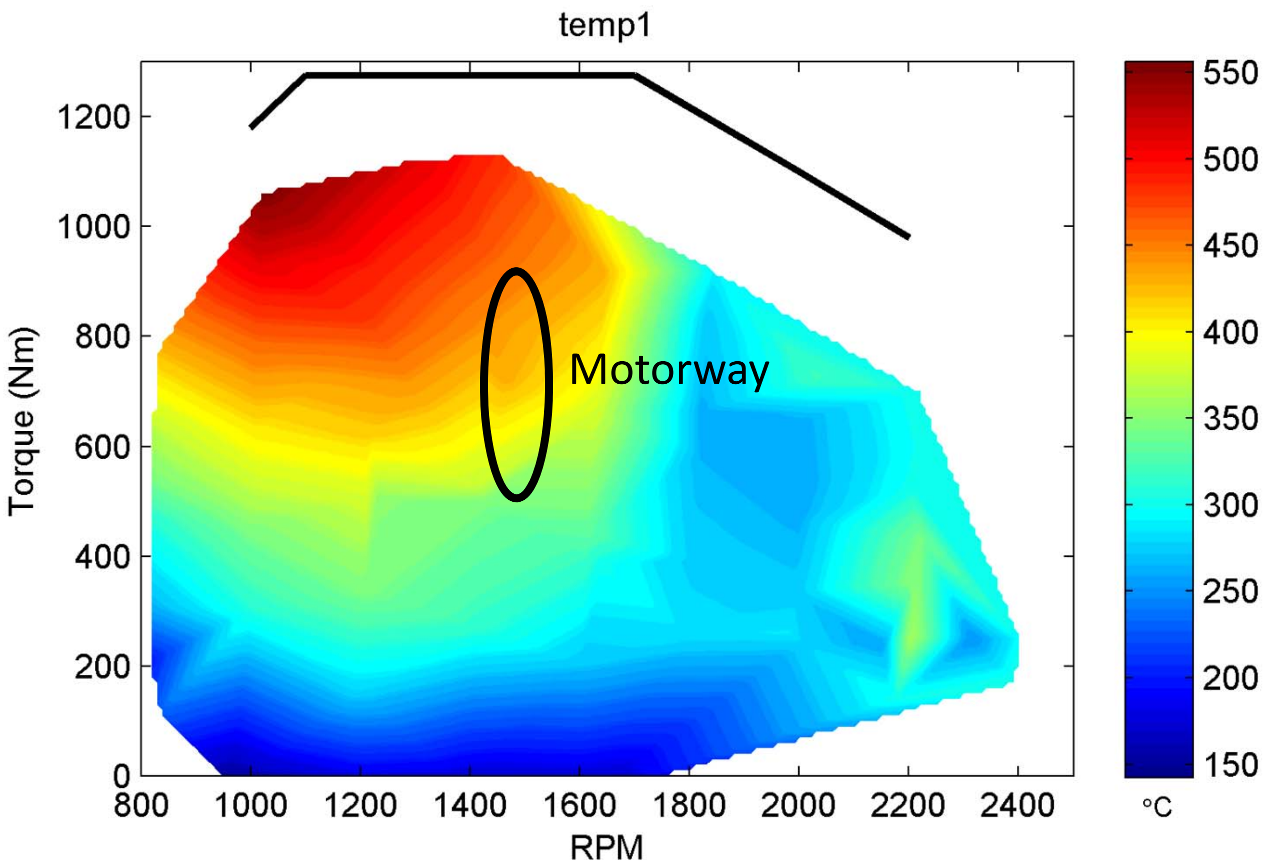
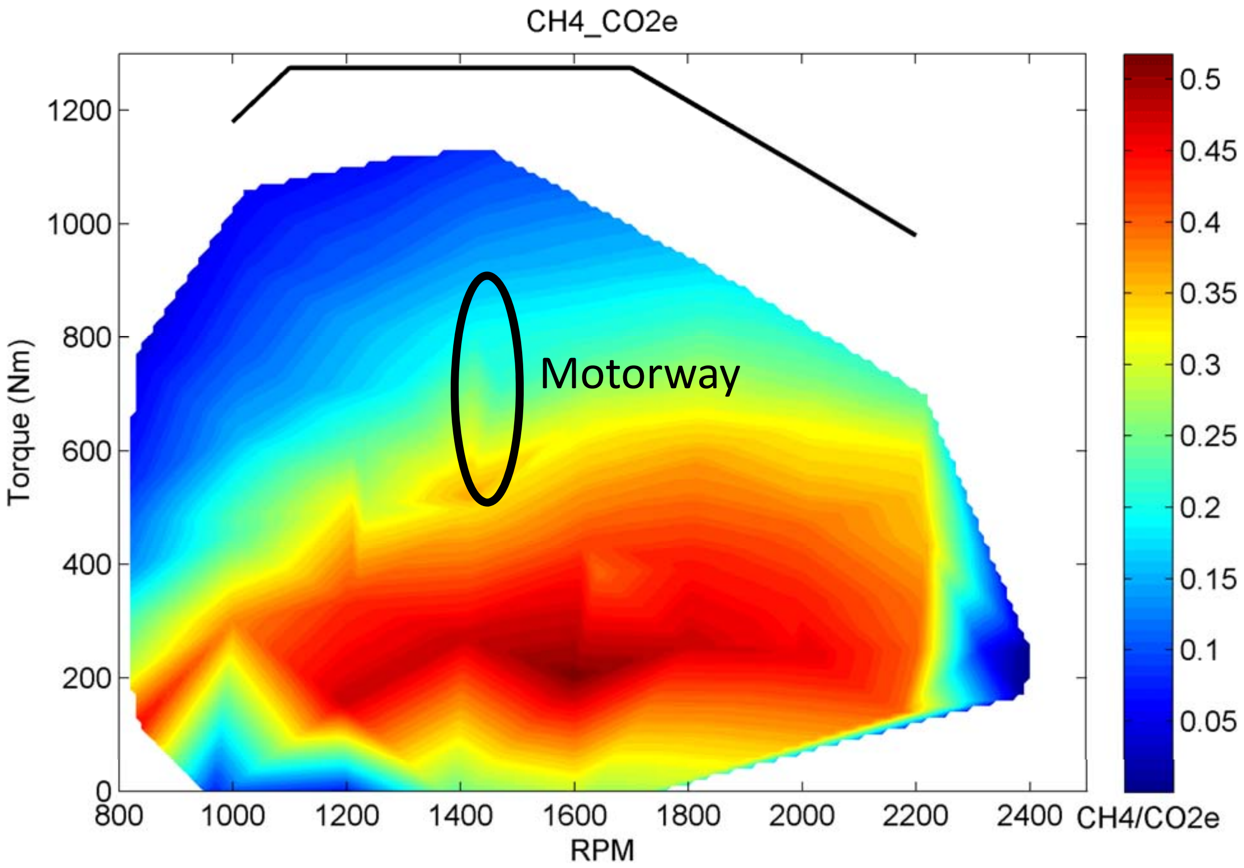
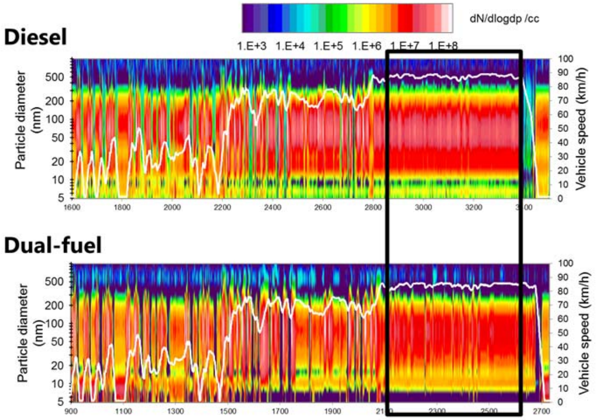


Potential of oxi cat on motorway

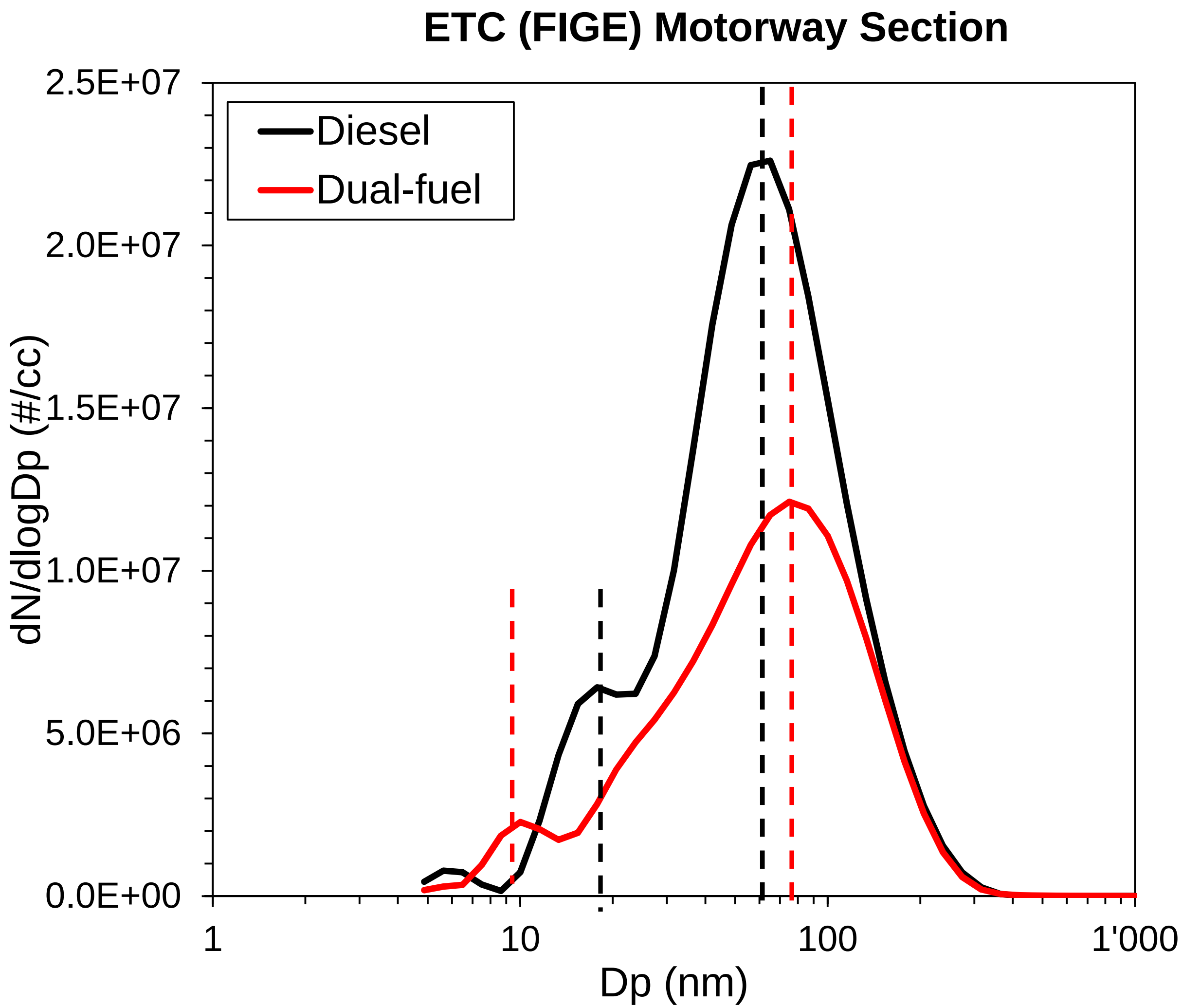


Could reduce CO2-e by 20-35% on motorway with addition of oxidation catalyst

Transient cycle (ETC) comparison

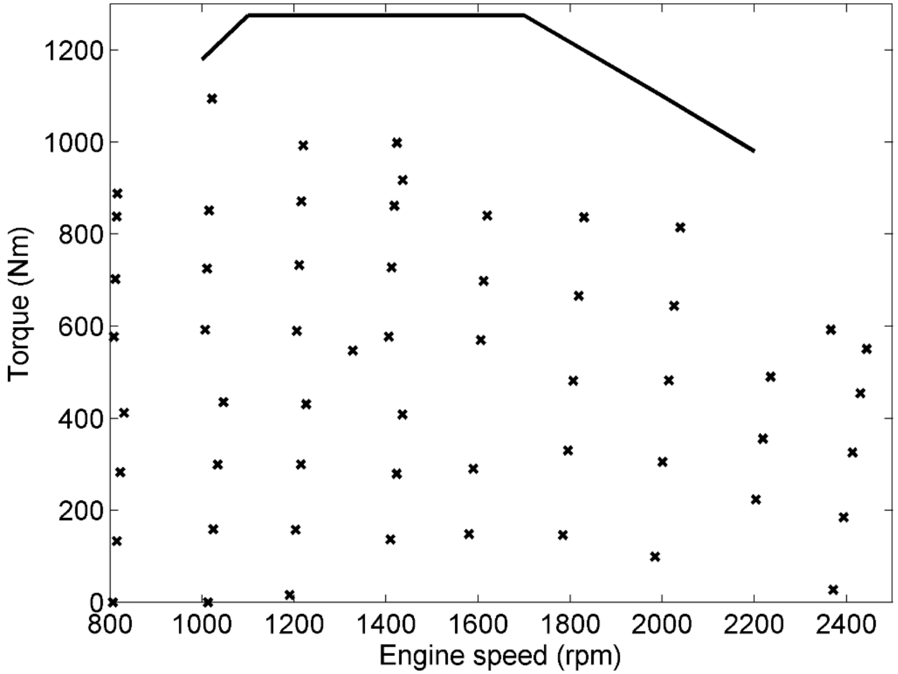


- Accumulation mode GMD increased from 65 nm to 75 nm
- Nucleation mode GMD decreased from 18 nm to 10 nm

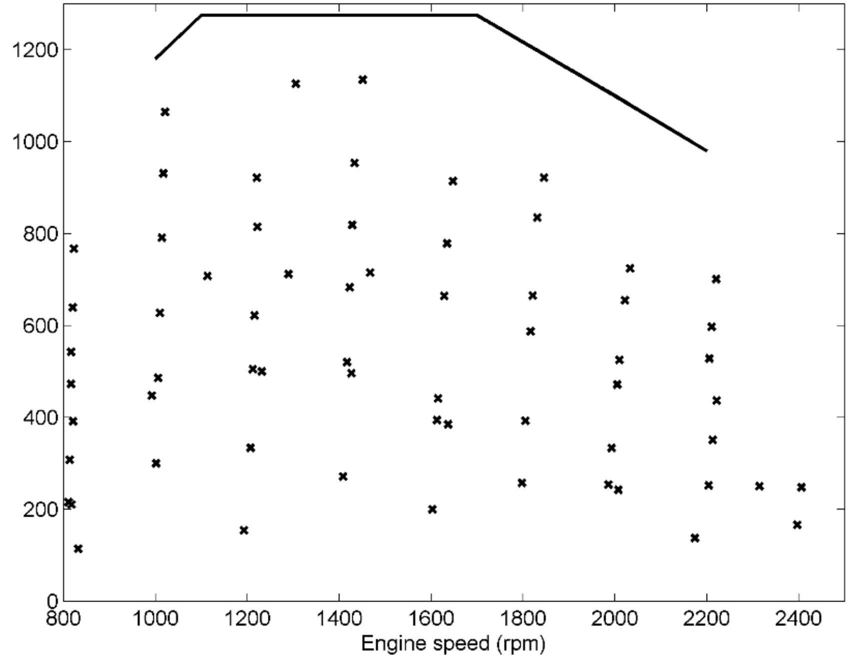


Steady-state test points

Diesel



Dual-fuel



Global warming potential (GWP)

- Metric to sum the impact of different greenhouse gases on a scale relative to CO_2 over a ‘time horizon’
- Quoted as “CO_2 equivalent”, CO_2e

Species	Time Horizon (years)		
	20	100	500
CO_2	1	1	1
CH_4	72	25	7.6

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M., and Waitz, I.A., 2010. Transport impacts on atmosphere and climate: Metrics. *Atmos. Environ.*, 44 (37), 4648–4677.