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

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

No Change Since 1986

Source: Lastauto Omnibus
Testberichte 1967 - 2009

Data Courtesy Daimler
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% CO₂ reduction
  - Improvements in air pollution?
- UK Low Emission HGV Task Force
  - £9.5M government support
  - Vehicles and infrastructure
Dual-fuel conversion systems

- Prins Diesel-blend
- Aftermarket ‘upgrade’
Dual-fuel conversion systems

- Prins Diesel-blend
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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

- Coriolis flow meter
- Exhaust
- SCR
- Tailpipe
- Heated PTFE (190°C)
- Gas analysers (engine out): CO, HC, NO\textsubscript{x}, CO\textsubscript{2}
- Gas analysers (tailpipe): CO, HC, NO\textsubscript{x}, CO\textsubscript{2}, FTIR
- Connection to Millbrook system
- Thermocouple
Experimental schematic

Coriolis flow meter

Exhaust

SCR

Diluter (~70:1)

Heated PTFE (190°C)

Gas analysers (engine out)
CO, HC, NOx, CO2

Gas analysers (tailpipe)
CO, HC, NOx, CO2, FTIR

Catalytic Stripper

1A
SMPS (3025)
CPC3022

1B
CO2 NDIR

Stainless steel (6.35 mm OD)

Tailpipe

Connection to Millbrook system

Thermocouple
Experimental schematic

Exhaust

Diluter (~70:1)

Gas analysers (engine out)
- CO, HC, NO\textsubscript{x}, CO\textsubscript{2}

Heated PTFE (190°C)

Gas analysers (tailpipe)
- CO, HC, NO\textsubscript{x}, CO\textsubscript{2}
- FTIR

SCR

Diluter (~70:1)

Catalytic Stripper

1A
- SMPS (3025)
- CPC3022

1B
- CO2 NDIR

2A
- CPC3776

2B
- CO2 NDIR

2C
- DMS500

Coriolis flow meter

Stainless steel (6.35 mm OD)

Connection to Millbrook system

Thermocouple

Connection to Millbrook system

Thermocouple
Test points

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

\[ \text{Energy substitution ratio} = \frac{\text{energy}_{\text{nat gas}}}{\text{energy}_{\text{nat gas}} + \text{energy}_{\text{diesel}}} \]
CO$_2$ emissions

**Diesel**

-10% CO$_2$ @ 1500 rpm, 600 Nm

**Dual-fuel**

C:H ratio + 50% natural gas $\rightarrow$ -12% CO$_2$
Tailpipe NOx

Diesel

Dual-fuel

-44% NOx @ 1500 rpm, 600 Nm

EURO V limit: 2.0 g/kWh (ESC)
Tailpipe CO

Diesel

Dual-fuel

x10 CO @ 1500 rpm, 600 Nm

EURO V limit: 1.5 g/kWh
Particle number emissions

Diesel

-60% particle number @ 1500 rpm, 600 Nm
DMS500 (5-1000 nm)

Dual-fuel
Accumulation mode PN

Diesel

Dual-fuel

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

DMS500

[EURO VI limit $8 \times 10^{11}$ part/kWh (>23 nm)]
Accumulation GMD

Significant increase in accumulation mode GMD after dual-fuel conversion
55-70 nm → 65-85 nm
- European transient cycle (ETC, or FIGE)
Transient cycle (ETC) comparison

**Diesel**

![Graph showing particle diameter and vehicle speed for Diesel](image)

**Dual-fuel**

![Graph showing particle diameter and vehicle speed for Dual-fuel](image)
Transient cycle (ETC) comparison

Diesel

Dual-fuel
Transient cycle (ETC) comparison

ETC (FIGE) Motorway Section

- Diesel
- Dual-fuel
• Accumulation mode GMD increased from 65 nm to 75 nm
Transient cycle (ETC) comparison

**Diesel**

**Dual-fuel**
• 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$_2$e

Diesel

Dual-fuel

+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 CH₄)
- Ash particles:
Further work

- Methane oxidation catalysts
- Crankcase emissions (particles and CH$_4$)
- Ash particles:
Further work

- Methane oxidation catalysts
- Crankcase emissions (particles and CH₄)
- Ash particles:

![Graphs showing particle distribution under different loads and engine conditions.](image-url)
Acknowledgements

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

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

- Pilot diesel injection provides ‘spark’
- Gas ‘fumigation’
- CO₂ emissions depend on
  - C:H ratio of fuel
    - Diesel: \( \approx C_{12}H_{22}, \text{ i.e. } 1:1.85 \)
    - Methane: CH₄, i.e. 1:4 (-24%)
  - Energy substitution ratio

94% of FIGE transient drive cycle covered by steady-state test points
CH₄ contribution to CO₂e
Engine out NOx

Diesel

Dual-fuel

-33% NOx @ 1500 rpm, 600 Nm

EURO V limit: 2.0 g/kWh
Nucleation mode PM

Diesel

Dual-fuel
Nucleation GMD

Diesel

Dual-fuel
Oxidation catalyst activity

- Johnson Matthey
  - Patent No. W02009106849

![CH₄ Oxidation Activities of Pd and Au/Pd Catalysts](image_url)
Exhaust temperatures
Exhaust temperatures

![Exhaust Temperatures Diagram](image-url)

- **Torque (Nm)** vs **RPM**
- **temp1**
- **Motorway**

°C
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 CO₂ over a ‘time horizon’
- Quoted as “CO₂ equivalent”, CO₂e

<table>
<thead>
<tr>
<th>Species</th>
<th>Time Horizon (years)</th>
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<tbody>
<tr>
<td></td>
<td>20</td>
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<tr>
<td>CO₂</td>
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<tr>
<td>CH₄</td>
<td>72</td>
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