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
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](http://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

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% $CO_2$ 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

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- Aftermarket ‘upgrade’
Outline

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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

Connection to Millbrook system

T Thermocouple

Tailpipe

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

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

Heated PTFE (190°C)
Experimental schematic

- **Coriolis flow meter**
- **Exhaust**
- **T1**
- **T2**
- **SCR**
- **Diluter (~70:1)**
- **Heated PTFE (190°C)**
- **Gas analysers (engine out)**
  - CO, HC, NO<sub>x</sub>, CO<sub>2</sub>
- **Gas analysers (tailpipe)**
  - CO, HC, NO<sub>x</sub>, CO<sub>2</sub>, FTIR
- **Catalytic Stripper**
- **1A**
  - SMPS (3025)
  - CPC3022
- **1B**
  - CO2 NDIR
- **Stainless steel (6.35 mm OD)**
- **Connection to Millbrook system**
- **Thermocouple**
Experimental schematic

Coriolis flow meter

Exhaust

Heated PTFE (190°C)

SCR

Diluter (~70:1)

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

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

Catalytic Stripper

1B
CO2 NDIR

2A
CPC3776

2B
CO2 NDIR

1A
SMPS (3025)

CPC3022

CPC3022

2C
DMS500

Stainless steel (6.35 mm OD)

Connection to Millbrook system

T Thermocouple

Tailpipe
Test points

- Steady state
- European transient cycle (ETC, or FIGE)
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- What is dual-fuel?

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Substitution ratio

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

Diesel

Dual-fuel

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

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

-44% NOx @ 1500 rpm, 600 Nm

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

**Diesel**

x10 CO @ 1500 rpm, 600 Nm

**Dual-fuel**

20 g/kWh

**EURO V limit: 1.5 g/kWh**
-60% particle number @ 1500 rpm, 600 Nm
DMS500 (5-1000 nm)
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
Transient cycle

- European transient cycle (ETC, or FIGE)
Transient cycle (ETC) comparison

**Diesel**

**Dual-fuel**
Transient cycle (ETC) comparison

**Diesel**

**Dual-fuel**

Vehicle speed (km/h)

Particle diameter (nm)

\[ \frac{dN}{d\log dp} / \text{cc} \]
Transient cycle (ETC) comparison

ETC (FIGE) Motorway Section

- **Diesel**
- **Dual-fuel**
Transient cycle (ETC) comparison

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

Diesel

Dual-fuel
**Transient cycle (ETC) comparison**

- 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 ($\sim$-44%)
  - Increase CO ($\sim$x10)
  - Reduce particle number (5-1000 nm, $\sim$-60%)
  - Increase GMD of accumulation mode
  - Increase total GHG (CO2e) by $\sim$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 CH₄)
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Further work

- Methane oxidation catalysts
- Crankcase emissions (particles and CH₄)
- Ash particles:
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’
- $\text{CO}_2$ emissions depend on
  - C:H ratio of fuel
    - Diesel: $\approx C_{12}H_{22}$, i.e. 1:1.85
    - Methane: $\text{CH}_4$, i.e. 1:4 (-24%)
  - Energy substitution ratio

Test points

- 94% of FIGE transient drive cycle covered by steady-state test points
$\text{CH}_4$ contribution to $\text{CO}_2e$
Engine out NOx

Diesel

-33% NOx @ 1500 rpm, 600 Nm

EURO V limit: 2.0 g/kWh

Dual-fuel
Accumulation/Nucleation

Diesel

Dual-fuel
Nucleation mode PM

Diesel

Dual-fuel
Nucleation GMD

Diesel

Dual-fuel
CH₄
Oxidation catalyst activity

- Johnson Matthey
  - Patent No. W02009106849
Exhaust temperatures

![Graph showing exhaust temperatures in relation to RPM and torque. The graph uses a color scale ranging from 150°C to 550°C.]
Exhaust temperatures

Motorway

Torque (Nm)

RPM

°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 CO$_2$ over a ‘time horizon’
- Quoted as “CO$_2$ equivalent”, CO$_2$e

<table>
<thead>
<tr>
<th>Species</th>
<th>Time Horizon (years)</th>
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<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>CO$_2$</td>
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</tr>
<tr>
<td>CH$_4$</td>
<td>72</td>
</tr>
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