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# Emissions Testing of Gas-Powered Commercial Vehicles

The results of tests to measure the greenhouse gas and air pollutant emission performance of various gas-powered HGVs, on behalf of Department for Transport.

Prepared by Low Carbon Vehicle Partnership

January 2017



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## Acknowledgements

The Low Carbon Vehicle Partnership are enormously grateful to the many individuals and organizations from industry and academia who contributed resources, vehicles and expertise to this study, as well as to the Department for Transport and Transport for London for funding it. Some, but by no means all those organizations are as indicated here.



*John Lewis Partnership*



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<b>Executive Summary .....</b>	<b>1</b>
<b>1 Introduction .....</b>	<b>7</b>
1.1 <i>Background</i> .....	7
1.2 <i>Programme management</i> .....	9
<b>2 Vehicles and technologies selected for testing .....</b>	<b>10</b>
<b>3 Test procedures and cycles .....</b>	<b>12</b>
3.1 <i>Test method</i> .....	12
3.2 <i>Instrumentation</i> .....	12
3.2.1 Air pollutant emissions .....	13
3.2.2 Greenhouse Gas emissions .....	13
3.3 <i>Test cycles</i> .....	15
<b>4 Test results.....</b>	<b>16</b>
4.1 <i>Greenhouse gas emissions</i> .....	16
4.1.1 Greenhouse gas emissions, dedicated gas vehicles .....	17
4.1.2 Greenhouse gas emissions, dual fuel vehicles .....	18
4.1.3 Nitrous oxide emissions .....	18
4.1.4 Overall GHG emissions summary .....	19
4.2 <i>Pollutant emissions</i> .....	21
4.2.1 Pollutant emissions, dedicated gas vehicles .....	21
4.2.2 Pollutant emissions, dual fuel vehicles.....	22
4.3 <i>Substitution rates and efficiency losses</i> .....	22
<b>5 Discussion .....</b>	<b>25</b>
5.1 <i>Greenhouse gas emissions</i> .....	25
5.1.1 Dedicated gas vehicles .....	25
5.1.2 Dual-fuel vehicles .....	26
5.2 <i>Future technology developments</i> .....	26
5.2.1 OEM dedicated gas technologies .....	27
5.2.2 OEM dual-fuel technologies .....	28
5.2.3 Retrofit dual-fuel conversions .....	29
<b>6 Conclusions &amp; Recommendations .....</b>	<b>31</b>
6.1 <i>Conclusions</i> .....	31
6.2 <i>Recommendations:</i> .....	32
<b>Glossary .....</b>	<b>33</b>
<b>Annex 1: LowCVP Accreditation Scheme Test Procedure.....</b>	<b>34</b>



## Executive Summary

### Background

Freight transport is vital to economic growth, but also has significant environmental impacts. Heavy goods vehicles (HGVs) are currently estimated to account for around 16% of UK greenhouse gas (GHG) emissions from road transport and around 21% of road transport NOx emissions, while making up just 5% of vehicle miles<sup>1</sup>. The 2008 Climate Change Act set an ultimate target for 2050 of an 80% reduction in GHG emissions from 1990 levels. Meeting this target will be challenging and the transport sector is under increasing pressure to decarbonize. Displacing conventional fuels with alternative fuels such as methane has the potential to significantly reduce GHG emissions from difficult-to-decarbonize sectors such as road freight.

There is considerable interest amongst fleet operators in the use of methane as a road fuel, either in its fossil fuel form as natural gas or as a biofuel, bio-methane. It attracts lower fuel duties than diesel and offers the potential for air quality (AQ) benefits and lower GHG emissions. However, there is currently a limited evidence base on the cost effectiveness, carbon abatement potential and wider impacts (e.g. air quality) of displacing diesel with methane in commercial vehicles.

The £11.3 million Low Carbon Truck Trial (LCTT)<sup>2</sup>, which ran between 2012 and 2016, part-funded industry consortia to purchase and trial around 370 alternatively-fuelled commercial vehicles (most of which were dual fuel, diesel/natural gas aftermarket conversions), and to commission refuelling infrastructure. Nearly all the vehicles trialled were Euro V but the Trial came at a time when the commercial vehicle market was making the major shift (and investment) to Euro VI. Euro VI gas-fuelled trucks were unavailable until towards the end of the trial period and the project was therefore unable to gather comprehensive evidence on the emissions performance of these vehicles. Evidence to date strongly supports the view that the shift to Euro VI has led to very significant reductions in pollutant emissions, including NOx, for conventional diesel vehicles.

### Methane Slip

Furthermore, the LCTT has indicated, via a limited, non-standardized set of tests by some of the participating consortia, but not through systematic measurement, that there has been an issue with emissions of unburnt methane (methane slip) from some of the participating vehicles, particularly the retrofit dual-fuel diesel/natural gas conversions. Methane is a potent GHG and if emissions are significant, they could outweigh any reductions in CO<sub>2</sub> emissions from using gas in place of diesel. Measurement of methane emissions was outside the scope of the LCTT and, more generally, there is currently a lack of real-world data on both methane slip and air quality pollutant emissions from dedicated gas and dual-fuel commercial vehicles.

In the first phase of research into this methane slip issue, a DfT research project in 2014/15 designed and trialled an HGV emissions testing protocol and made recommendations for further tests. That research, by Ricardo-AEA, also explored the causes of methane slip and summarized previous research into the phenomenon. It showed how well designed and calibrated spark

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<sup>1</sup> <https://www.gov.uk/government/collections/transport-statistics-great-britain#data-tables> - 2014 data, calculated from Tables TSGB0306 (ENV0202), TSGB0308 (ENV0301) and TSGB0701 (TRA0101).

<sup>2</sup> At the time of drafting, the final report into the LCTT was also in draft. The latest published summary is available via [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/448049/low-carbon-truck-trial-2.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/448049/low-carbon-truck-trial-2.pdf)

ignition engines, running on dedicated gas, combined with exhaust after-treatment catalysis can minimize methane slip. It also highlighted how dual fuel, diesel/natural gas engines could be particularly susceptible to methane slip<sup>3</sup>.

The Ricardo-AEA report also noted how methane emissions are regulated via the type approval process for dedicated gas engines, but not for aftermarket conversions to dual-fuel operation. The report estimated that methane emissions higher than about 2.6 g/km would, for the converted vehicles typically operating in the LCTT, be sufficient to cancel out the reported reductions in CO<sub>2</sub> emissions. Furthermore, it highlighted how little research had already been carried out internationally into the methane slip issue, with previous studies using differing and therefore not directly comparable approaches to measuring methane emissions, and thus there was a need to develop and use a representative, standardized test protocol.

### **Vehicle Testing**

As a second, follow-up phase, the DfT commissioned this HGV emissions testing project with the Low Carbon Vehicle Partnership (LowCVP) and its members to carry out vehicle testing across a representative range of gas-fuelled HGVs to quantify the scale of the methane slip issue and to identify possible mitigation options. This programme of testing was designed to help the Department for Transport to develop its evidence base to inform future policy on gas vehicles, and allow the results of the Low Carbon Truck Trial to be set in their proper GHG impacts context.

With due consideration given to the priorities identified, the funding available and the availability of vehicles and technologies, the tests covered the following vehicles/technologies:

- Four dedicated OEM Euro VI natural gas vehicles, including two 40t artics, one 18t rigid and one 7t van
- One LCTT dual fuel (DF) diesel/natural gas retrofit conversion to a Euro V 44t artic vehicle
- One DF (diesel/natural gas) retrofit conversion to a Euro VI 44t artic vehicle
- One DF (diesel/LPG) retrofit conversion to a Euro VI 44t artic vehicle<sup>4</sup>

To provide proper baseline data, each dedicated gas vehicle was evaluated against an equivalent, conventional Euro VI diesel truck. The baseline case for the dual fuel vehicles was provided by comparing emissions performance under dual fuel operating conditions with those when the same vehicle was operating in diesel-only mode.

The test programme used the track-based test procedures and three drive cycles developed originally by LowCVP for its HGV retrofit (CO<sub>2</sub> reducing) technology accreditation scheme (simulating long haul, regional delivery and urban delivery operations), with emissions measurement via Portable Emissions Monitoring System (PEMS). A fourth, city-centre delivery cycle was also developed as part of the programme to better represent operations typical of trucks delivering into congested city centres.

It was thought at the outset of the research that nitrous oxide (N<sub>2</sub>O) was likely to be emitted in very low (and similar) quantities from both diesel and gas-fuelled vehicles. During the project,

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<sup>3</sup> *Provision of HGV Emissions Testing: Final Report*. Ricardo-AEA, August 2015. Available via [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/468172/hgv-emissions-testing.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/468172/hgv-emissions-testing.pdf)

<sup>4</sup> As LPG was considered outside of the original scope of the (methane) work funded by DfT, funding for testing of this technology was provided directly by the technology supplier.

however, evidence began to emerge from stakeholders consulted and other sources that emissions of nitrous oxide, which are currently unregulated in Europe and unmeasured in vehicle certification, may not be as uniformly low (and inconsequential to an overall GHG assessment) as previously thought. In particular, the suggestion was that diesel-powered vehicles equipped with Selective Catalytic Reduction (SCR) technology (typical of Euro VI specifications) may be prone to emitting sufficient quantities of nitrous oxide to materially affect their overall GHG impacts. Nitrous oxide has a 100-year GWP of 298 (current GHG reporting guidelines), an order of magnitude greater than methane.

The available evidence, albeit for bus engines operating to bus duty cycles, indicated that nitrous oxide emissions from Euro VI diesel trucks may add of the order of 5 – 10% to their overall GHG impacts. This has potentially significant implications for freight carbon reduction strategies and greenhouse gas reporting (beyond the scope of this study) but also has the potential to quite significantly increase the relative overall GHG savings available from gas-powered vehicles. Although constrained by available time and budget, a limited programme of further, chassis-dyno testing was commissioned to obtain additional data on the nitrous oxide issue, specifically from commercial vehicles operating to freight-relevant duty cycles.

### **GHG Results Summary**

For the dedicated natural gas vehicles, the GHG results are somewhat mixed. When comparing with a substantially higher-powered diesel vehicle (Dedi02), overall savings of 4-8% were measured, but in more like-for-like tests (Dedi01 and Dedi03), the savings were, at best, 5% and, at worst, the dedicated gas vehicle's emissions were some 15% higher than the diesel comparator. These results suggest that there are quite high efficiency losses under some operating conditions in moving from a compression ignition, conventional diesel engine to a spark-ignition one of similar power output.

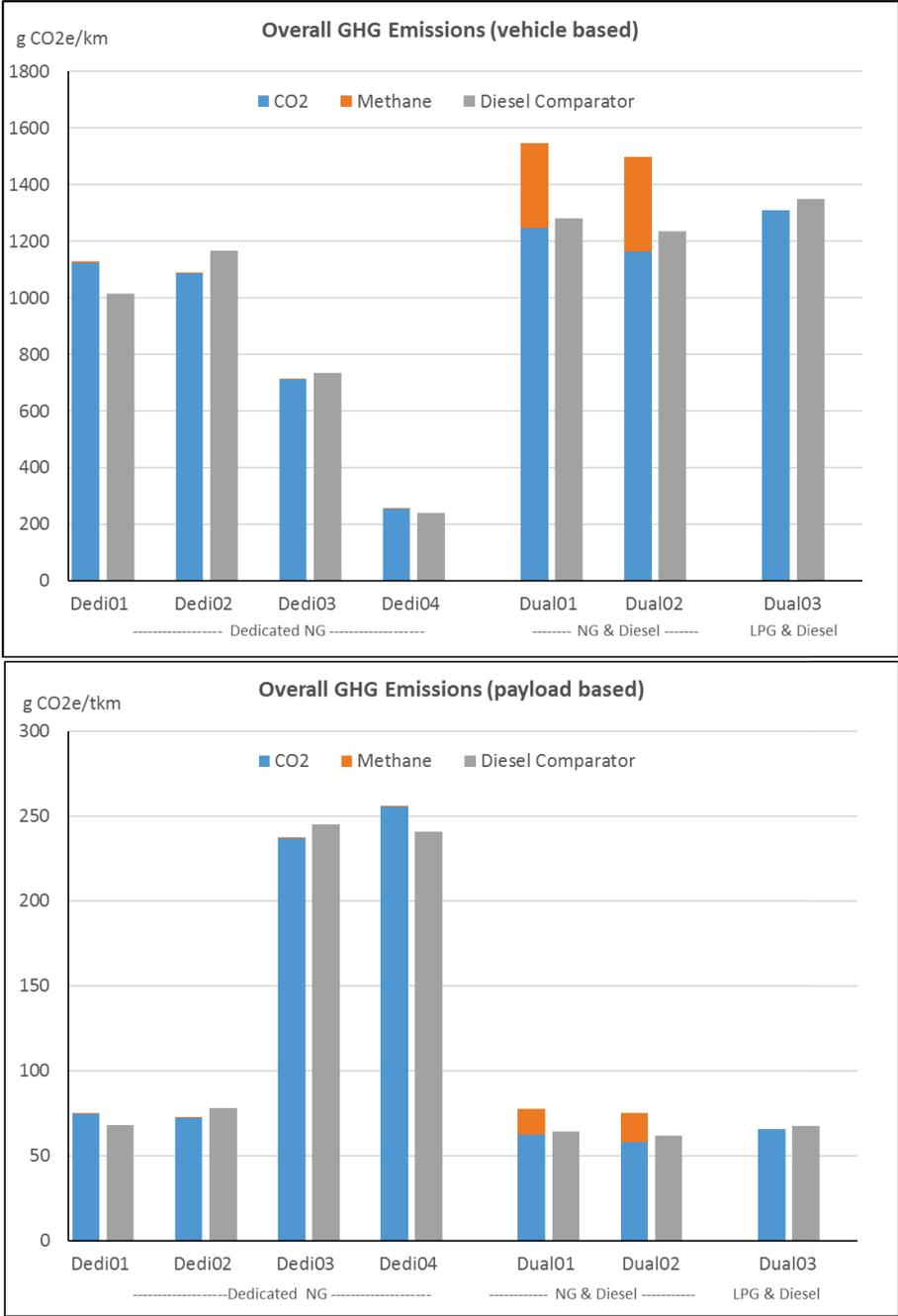
None of the dedicated gas vehicles tested were found to emit significant quantities of methane, i.e. there was, for these vehicles, little evidence of any methane slip. The highest levels of methane detected were from the two articulated vehicles when operating under the long haul test cycle, but even under these conditions the quantities involved were of the order of just 0.2 – 0.5 g/km, which on a CO<sub>2</sub> equivalence basis only increased the overall GHG emissions by about 1% compared to considering only the CO<sub>2</sub> emissions.

For the current-generation dual-fuel vehicles operating on diesel and natural gas, levels of methane slip were found to be substantial under all test cycles (9 – 18 g/km). When considering only tailpipe CO<sub>2</sub> emissions, both these retrofit conversions (Dual01 to a Euro VI diesel and Dual02 to a Euro V) showed savings of between 4% and 11%, findings very much in line with those of the Low Carbon Truck Trial. When factoring in the measured methane slip, however, the overall GHG impacts of the dual-fuel vehicles rise by, on average, 26% for the Euro VI conversion and 37% for the older Euro V system, thus turning the CO<sub>2</sub> "savings" into overall GHG increases over the diesel-only baselines of around 10 – 35%.

The dual-fuel diesel and LPG retrofit conversion (of a Euro VI diesel tractor unit) also showed quite high levels of hydrocarbon (THC) emissions (1 – 2 g/km). These emissions are presumed unburnt fuel, in this case LPG, not methane, and thus do not contribute to the overall GHG impacts. This system generally achieved modest, but measurable, average GHG savings of 2%.

The non-SCR-equipped vehicles tested exhibited low levels of nitrous oxide emissions. For the dedicated gas vehicle, there were no such emissions. For the non-SCR diesel vehicles, N<sub>2</sub>O emissions of around 1 - 10 mg/km were measured, sufficient to increase the overall GHG impacts of such vehicles by around 0.4 – 0.8%. The two SCR-equipped Euro VI vehicles tested showed higher levels of N<sub>2</sub>O emissions than the non-SCR versions, at levels high enough to add about 1 – 2% to the overall GHG impacts.

Graphical summaries of the overall GHG emissions from all the tested vehicles are shown in the Figures below. For ease of presentation, the results from all test cycles for each vehicle have been averaged, and the contribution, if any, from methane slip converted into g CO<sub>2</sub>e. The chart on the top presents the averaged data on a vehicle basis, in grams of CO<sub>2</sub> equivalent per vehicle kilometre travelled. The lower chart normalizes this same data by payload carried, in grams of CO<sub>2</sub> equivalent per tonne-kilometre of goods moved.



## **NOx and Other Pollutants Results Summary**

The Euro VI dedicated gas vehicles tested produced, on average, NOx emissions of about 135 mg/km, while the Euro VI diesel comparators produced, on average, about 230 mg/km. Testing for statistical significance, the results are sufficient to conclude that Euro VI dedicated gas vehicles emit lower levels of NOx than their diesel counterparts. The same is true for NO<sub>2</sub> emissions with the gas vehicles producing about 20 mg/km on average, less than one-third of the 78 mg/km produced, on average, by the diesel comparators. Emissions of carbon monoxide, however, were typically higher for the dedicated gas vehicles than their diesel equivalents. Emissions of hydro-carbons (THC, unburnt fuel) were also higher.

For the dual fuel, diesel and natural gas conversion of a Euro VI vehicle (Dual01), the NOx emissions were, on average, higher in dual-fuel mode than with the same vehicle operating in diesel-only mode, but the CO levels were lower. For the diesel and LPG conversion of a Euro VI vehicle (Dual03), the NOx emissions were lower than when in diesel-only mode but the CO emissions were higher. These differences, as well as the THC (unburnt gas) emissions, suggest that current applications of retrofit dual-fuel technologies do involve some compromises with regard to the overall ability of the vehicles' exhaust after-treatment systems to fully mitigate emissions of all the regulated pollutants.

The after-market conversion of a Euro V vehicle (Dual02) produced statistically significantly lower NOx emissions in dual-fuel mode than when operated in diesel-only mode, but emissions of CO were much higher. These data indicate first, that such compromises in overall pollutant emissions control seem to have been necessary at the more basic Euro V levels too and, second, that the move to Euro VI has, for these diesel vehicles, been effective in cutting overall NOx emissions by over 98% from Euro V levels. The test programme suggests that a further move from Euro VI diesel vehicles to Euro VI dedicated gas increases the magnitude of that reduction in NOx emissions to at least 99%.

**Conclusions:** (Note these are based on a limited programme of tests, on a limited number of vehicles, so care is needed if extrapolating the results to a UK-wide level. The data presented are based on actual tailpipe emissions and take no account of the GHG benefits of bio-fuel options):

### **Methane & CO<sub>2</sub> emissions**

- The Euro VI dedicated gas vehicles tested through this programme exhibit very low levels of methane slip, typically adding less than 0.5% to the overall GHG impacts of those vehicles compared with the CO<sub>2</sub>-only case.
- Current generation (Euro VI) dedicated gas vehicles, running on natural gas (rather than bio-methane), are likely to have broadly similar GHG impacts compared to Euro VI diesel equivalents, to within +/- 10%.
- The only after-market dual fuel system currently available, converting a Euro VI diesel truck to diesel and natural gas operation, exhibited high levels of methane slip (sufficient to increase GHG emissions by c. 20%).
- An after-market dual fuel diesel and LPG system (conversion of Euro VI diesel) exhibited similarly modest GHG benefits to some of the dedicated gas vehicles tested (c. 5% savings), and although some slippage of hydro-carbons was evident, this is unburnt LPG, not methane or any other GHG. The system tested has since undergone a software update that may well reduce the levels of hydro-carbon emissions.

- The after-market dual fuel (diesel/CNG) conversion of a Euro V vehicle exhibited high levels of methane slip (sufficient to increase GHG emissions by c. 20-30%).
- Effective catalysis of methane is possible, as is more effective in-cylinder methane combustion. Two current Innovate UK/OLEV-funded projects are developing new retrofit dual-fuel systems. At least one OEM is developing its own dual fuel (diesel-methane) system.

### **Nitrous Oxide**

- The research has not yet been able to disprove the hypothesis that Euro VI diesel trucks typically emit quite high levels of N<sub>2</sub>O. Further evidence is needed to quantify this.
- The tests show that N<sub>2</sub>O emissions are very low for the dedicated gas vehicle and the two non-SCR equipped diesel vehicles tested, but higher for the two SCR equipped diesel vehicles tested (both ≤ 7.5t gwv), sufficient to add 1 – 2% to those vehicles' overall GHG impacts.
- For light duty vehicles, other technologies are known to exist that can deal with NO<sub>x</sub> emissions without producing significant quantities of N<sub>2</sub>O, but SCR is the primary technology currently available for heavy-duty diesel vehicles to comply with Euro VI emissions standards.

### **Air pollutants**

- Euro VI dedicated gas vehicles emitted lower levels of NO<sub>x</sub> than their diesel counterparts. The same is true if only NO<sub>2</sub> emissions are considered. Emissions of carbon monoxide and hydro-carbons, however, were typically higher.
- The testing indicates that the transition to Euro VI has, for diesel heavy goods vehicles, been effective in cutting overall NO<sub>x</sub> emissions by over 98% when compared to Euro V vehicles. A further move from Euro VI diesel vehicles to Euro VI dedicated gas increases that reduction in NO<sub>x</sub> emissions to at least 99%.
- The dual-fuel diesel and natural gas system retrofitted to a Euro VI diesel vehicle exhibited increases in average NO<sub>x</sub> emissions in dual-fuel mode compared its diesel-only mode. THC emissions also increased, but CO emissions were lower. The dual fuel diesel and LPG system retrofitted to a Euro VI diesel vehicle produced lower NO<sub>x</sub> emissions in its dual fuel mode compared to its diesel-only mode, but emissions of other pollutants (CO and THC) increased.
- The dual fuel (diesel and natural gas) system retrofitted to a Euro V vehicle consistently reduced NO<sub>x</sub> emissions but levels remain at least one order of magnitude higher than all the Euro VI vehicles tested (diesel, gas or dual fuel). Emissions of CO and THC increased.

### **Recommendations:**

- This study has shown that dedicated gas commercial vehicles have potential to deliver significant GHG savings when a non-fossil, bio- or synthetic methane blend is used. DfT should therefore continue to support the development of gas vehicle infrastructure and gas-powered vehicles, particularly dedicated gas, while increasing the supply of low carbon/renewable methane as a sustainable transport fuel.
- This study has highlighted the potential for GHG savings from dual fuel diesel/LPG conversions, and the role of bio-LPG. DfT should also, therefore, consider enhancing its support mechanisms for this sustainable transport fuel.
- DfT should fund further research into N<sub>2</sub>O emissions from Euro VI diesel vehicles > 7.5t gwv.
- DfT should continue to develop its evidence on GHG and AQ performance of emerging commercial vehicle technologies.

# 1 Introduction

## 1.1 Background

Freight transport is vital to economic growth, but also has significant environmental impacts. Heavy goods vehicles (HGVs) are currently estimated to account for around 16% of UK greenhouse gas (GHG) emissions from road transport and around 21% of road transport NO<sub>x</sub> emissions, while making up just 5% of vehicle miles<sup>5</sup>. The 2008 Climate Change Act set an ultimate 2050 target of an 80% reduction in GHG emissions from 1990 levels. Meeting this target will be challenging and the transport sector is under increasing pressure to decarbonize.

In addition, the 2008 ambient air quality directive (2008/50/EC) sets legally binding limits for concentrations of major pollutants that impact public health such as particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>) and nitrogen dioxide (NO<sub>2</sub>). As one of a range of measures to ensure the UK meets legal limit values for nitrogen dioxide in the UK, some older polluting vehicles, including lorries, will be discouraged from entering a number of city-centres through the implementation of Clean Air Zones<sup>6</sup>. The Government is considering additional measures to meet legal limits for nitrogen dioxide and will set out further plans in 2017.

Displacing conventional fuels with alternative fuels such as methane has the potential to significantly reduce GHG emissions from difficult-to-decarbonize sectors such as road freight. There is considerable interest amongst fleet operators in the use of methane, either in its fossil fuel form as natural gas or as a biofuel, bio-methane. It attracts lower fuel duties than diesel and offers the potential for air quality benefits and lower GHG emissions. However, there is currently a limited evidence base on the cost effectiveness, carbon abatement potential and wider impacts (e.g. air quality) of displacing diesel with methane in commercial vehicles.

The £11.3 million Low Carbon Truck Trial<sup>7</sup> (LCTT), which ran between 2012 and 2016, part-funded industry consortia to purchase and trial around 370 alternatively-fuelled commercial vehicles (most of which were dual fuel, diesel/natural gas aftermarket conversions), and to commission refuelling infrastructure. Nearly all the vehicles trialled were Euro V but the Trial came at a time when the commercial vehicle market was making the major shift (and investment) to Euro VI. Euro VI gas-fuelled trucks were unavailable until towards the end of the trial period and the project was therefore unable to gather comprehensive evidence on the emissions performance of these vehicles. Evidence to date strongly supports the view that the

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<sup>5</sup> <https://www.gov.uk/government/collections/transport-statistics-great-britain#data-tables> - 2014 data, calculated from Tables TSGB0306 (ENV0202), TSGB0308 (ENV0301) and TSGB0701 (TRA0101).

<sup>6</sup> [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/486636/aq-plan-2015-overview-document.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/486636/aq-plan-2015-overview-document.pdf)

<sup>7</sup> At the time of drafting, the final report into these Trials was also in draft. The latest published summary is available via [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/448049/low-carbon-truck-trial-2.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/448049/low-carbon-truck-trial-2.pdf)

shift to Euro VI has led to very significant reductions in pollutant emissions, including NOx for conventional diesel vehicles.

Furthermore, the Trial has indicated, via a limited, non-standardized set of tests by some of the participating consortia, but not through systematic measurement, that there has been an issue with emissions of unburnt methane (methane slip) from some of the participating vehicles, particularly the retrofit dual-fuel diesel/natural gas conversions. Methane is a potent GHG and if emissions are significant, they could outweigh any reductions in CO<sub>2</sub> emissions from using gas in place of diesel. Measurement of methane emissions was outside the scope of the LCTT and, more generally, there is currently a lack of real-world data on both methane slip and air quality pollutant emissions from gas and dual-fuel commercial vehicles.

In the first phase of research into this methane slip issue, a DfT research project in 2014/15 designed and trialled an HGV emissions testing protocol and made recommendations for further tests<sup>8</sup>. That research, by Ricardo-AEA<sup>9</sup>, also explored the causes of methane slip and previous research into the phenomenon. It showed how well designed and calibrated spark ignition engines, running on dedicated gas, combined with exhaust after-treatment catalysis can minimize methane slip. It also highlighted how dual fuel (diesel/gas) engines could be susceptible to relatively high levels of methane slip.

The Ricardo-AEA report also noted how methane emissions are regulated via the type approval process for dedicated gas engines, but not for aftermarket conversions to dual-fuel operation. The report estimated that methane emissions higher than about 2.6 g/km would, for the converted vehicles typically operating in the LCTT, be sufficient to cancel out the reported reductions in CO<sub>2</sub> emissions. It also highlighted how what little research had already been carried out internationally into the methane slip issue, had followed a variety of different approaches and thus there was a need to develop and use a representative, standardized test protocol.

As a second, follow-up phase, the DfT commissioned this HGV emissions testing project with the Low Carbon Vehicle Partnership (LowCVP) to carry out vehicle testing across a representative range of available gas-fuelled HGVs to quantify the scale of the methane slip issue and to identify possible mitigation options. This programme of testing was designed to help DfT to develop its evidence base, inform future policy on gas vehicles, and allow the results of the Low Carbon Truck Trial to be set in their proper GHG impacts context.

To complement its LoCITY programme<sup>10</sup>, Transport for London (TfL) provided additional funds to test other vehicle technologies (the results of which will be reported separately) and to

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<sup>8</sup> *Provision of HGV Emissions Testing: Final Report*. Ricardo-AEA, August 2015. Available via [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/468172/hgv-emissions-testing.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/468172/hgv-emissions-testing.pdf)

<sup>9</sup> Ricardo-AEA have since changed their name to Ricardo – Energy & Environment. Ricardo-AEA is retained for the purposes of this report when referring to this earlier research

<sup>10</sup> [www.locity.org.uk](http://www.locity.org.uk)

develop a new city centre delivery test cycle, which was also used for some of the DfT-funded gas vehicle test programme, where appropriate.

It is important to emphasize that the testing was commissioned to measure tailpipe emissions of greenhouse gases and air quality pollutants only. Such measurements do not take into account any bio-content of the fuel, nor any well-to-tank emissions associated with different fuels and supply chains. The testing programme also excluded consideration of other potential benefits of gas-powered vehicles such as reduced noise; vehicle manufacturer tests have shown that natural gas engines are considerable quieter than their diesel equivalents.

## **1.2 Programme management**

The test programme was managed by LowCVP, who were responsible for the testing programme and for the delivery of this report, as well as all the day-to-day decisions, in conjunction with its funding partners, including DfT. The testing was carried out under contract to LowCVP by specialists at Millbrook and Horiba-Mira Ltd, on vehicles and technologies supplied by a wide range of industry partners, including OEMs, after-market converters and leading freight vehicle operators. All such participants were also invited to join a programme Steering Group, which was used to discuss and refine the detailed test plans and methodology as it progressed, as well as to peer review the emerging findings. In addition, a workshop, hosted by TfL, was held at the start of the project and provided an opportunity for various stakeholders to help shape and contribute to the programme to ensure both maximum support and relevance.

## 2 Vehicles and technologies selected for testing

The initial DfT-funded research to develop a test protocol, carried out and reported by what was then Ricardo-AEA, made recommendations about the future use of that protocol:

- Test currently available technologies
- Focus on future fleet, with an emphasis on Euro VI vehicles
- Focus on after-market conversions
- Also include OEM offerings, to continue to build the evidence base with them

In addition, it was decided that as DfT also have need for results of the Low Carbon Truck Trial to be set in their wider GHG context, some testing of vehicles deployed in the Trial would be desirable. The LCTT involved mainly diesel/gas dual-fuel retrofit technologies applied to what were originally conventional Euro V diesel vehicles.

The final report from the LCTT was being drafted at the same time as this one, but its provisional focus was on CO<sub>2</sub> emissions only, as calculated from the measured consumption of fuel and assuming full combustion. Its results do not take account of any emissions of unburnt methane (methane slip) experienced by the trial trucks, hence the need for this additional work.

Additionally, the LCTT utilized blends of bio-methane and reported overall GHG savings net of these blends. For the purpose of this HGV emissions testing programme all data has adopted a “raw tailpipe” assessment of the emissions and no account of bio-methane, bio-diesel or bio-LPG has been included in the data presented.

With due consideration given to the priorities identified, and the availability of vehicles and technologies at the time of testing, as well as the funding available, the gas vehicle tests covered the following vehicles/technologies:

- Four dedicated OEM Euro VI natural gas vehicles, including two 40t artics, one 18t rigid and one 7t van
- One LCTT dual fuel (DF) natural gas-diesel retrofit conversion to a Euro V 44t artic vehicle
- One DF (diesel/natural gas) retrofit conversion to a Euro VI 44t artic vehicle
- One DF (diesel/LPG) retrofit conversion to a Euro VI 44t artic vehicle<sup>11</sup>

To provide proper baseline data, each dedicated gas vehicle was evaluated against an equivalent, conventional Euro VI diesel truck. Specifications between dedicated gas and “equivalent” diesel trucks inevitably vary, however, for example in terms of engine power, torque and/or transmission systems. It was not possible to find exact matches, so the diesel comparators were chosen to match as closely as possible the dedicated gas vehicles, within the constraints of time and vehicle availability, which limits the validity of the diesel to dedicated

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<sup>11</sup> As LPG was considered outside of the original scope of the (methane) work funded by DfT, funding for testing of this technology was provided directly by the technology supplier.

gas comparisons. Any differences and their likely significance have been considered and are discussed in the results section of this report.

The baseline case for the dual fuel vehicles was provided by comparing emissions performance under dual fuel operating conditions with those when the same vehicle was operating in diesel-only mode giving, in this case, exact equivalence.

At the time of testing there were no other OEM Euro VI gas-fuelled vehicles available, nor any other dual fuel conversions to Euro VI base vehicles on the market. However, discussions with stakeholders identified that there are several products under development, which are relevant to the future of gas-based propulsion technologies. A discussion of the potential role for near-to-market technologies and for other technological innovations follows in section 5.2 of this report.



*Figure 1. Example of test process (Control vehicle in foreground, Test vehicle in background)*

## 3 Test procedures and cycles

### 3.1 Test method

The 2015 Ricardo-AEA work to develop a test protocol made the following main recommendations regarding the test method to be followed:

- Track testing was advocated over on-road tests, which were considered too difficult to achieve repeatability, or chassis dynamometer tests, which are expensive, with limited facility availability and load capacity and difficult to demonstrate to the satisfaction of the road freight industry that tests are genuinely representative of real-world conditions.
- Driving cycles should reflect real-world operations of the vehicles being tested, and the cycles for the test vehicles and their diesel/diesel-only comparators should be similar (at least in terms of average speeds and kinetic intensities).
- A combination of urban, rural and motorway driving conditions was likely to be suitable.
- PEMS equipment should be used for emissions analysis, with Total Hydrocarbons (THC) acceptable as a proxy for methane when running on natural gas, if a dedicated methane sensor was not available.

The programme management team agreed at the outset that the test procedures and three drive cycles developed originally by LowCVP for its HGV retrofit (CO<sub>2</sub> reducing) technology accreditation scheme, meet all of the above requirements and are thus compliant with Ricardo-AEA's recommended protocol. They thus formed the basis for this test programme<sup>12</sup>. A brief summary of the test protocol is included as Annex 1 of this report.

As well as using the scheme's back-to-back vehicle comparison method (testing the diesel baseline vehicle on one day and its gas-fuelled equivalent on another day), testing also followed the scheme's recommended practice of using a control vehicle on each test day to measure, and allow correction for, if necessary, any changes in ambient conditions affecting fuel consumption.

In accordance with the Ricardo-AEA protocol, the payload for each vehicle tested was generally set to be somewhere in the range 50 – 70% of the maximum permissible, and was accurately matched between the gas and diesel comparators to ensure both vehicles were doing equivalent work. For any given vehicle pair, the payload was identical for all test cycles.

### 3.2 Instrumentation

In accordance with the protocol recommendations and LowCVP accreditation scheme procedures, Portable Emissions Monitoring Systems (PEMS) were used. The two test houses

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<sup>12</sup> The test procedures and data analysis techniques developed for the accreditation scheme are available via [www.lowcvp.org.uk](http://www.lowcvp.org.uk)

used had slightly different PEMS equipment capabilities, but the core emissions monitoring, common to both, included the following:

- Carbon Monoxide, CO
- Carbon Dioxide, CO<sub>2</sub>
- Oxides of Nitrogen, NO<sub>x</sub>
- Total Hydrocarbons, THC

### **3.2.1**      *Air pollutant emissions*

Particulates (particle mass and particle number) were not measured, as current PEMS technology is not considered sufficiently robust to accurately and reliably measure them, particularly as in any event such emissions are likely to be very low due to the presence on all vehicles tested of particulate filters. Such filters have been shown by other research (including tests by TfL<sup>13</sup>) to be highly effective at reducing particulates.

Where possible, the NO<sub>x</sub> measurements were complemented with separate measures of Nitric Oxide (NO) and Nitrogen Dioxide (NO<sub>2</sub>), as the fraction emitted as primary NO<sub>2</sub> is known to be of particular concern from an air quality perspective.

As well as the direct measurement of the above tailpipe, pollutant emissions, fuel flow meters were used to accurately measure diesel fuel consumption. This allowed for the determination of substitution rates and efficiency losses in the dual fuel vehicles where the PEMS equipment gives only aggregated CO<sub>2</sub> emission levels.

### **3.2.2**      *Greenhouse Gas emissions*

Apart from CO<sub>2</sub> and CH<sub>4</sub> (measured using THC as a proxy for unburnt fuel), the other GHG of significant potential relevance to road transport is Nitrous Oxide (N<sub>2</sub>O). This was excluded from the track-based measurement because, and as reported by the 2015 Ricardo-AEA research, it is not currently possible to measure it accurately using portable emissions measuring equipment. It was also thought at the outset of the research that N<sub>2</sub>O was likely to be emitted in very low (and similar) quantities from both diesel and gas-fuelled vehicles.

During the project, evidence began to emerge from stakeholders consulted and other sources that emissions of nitrous oxide, which are currently unregulated in Europe and unmeasured in vehicle certification, may not be as uniformly low (and inconsequential to an overall GHG assessment) as previously thought. In particular, the suggestion was that diesel-powered vehicles equipped with Selective Catalytic Reduction (SCR) technology may be prone to emitting sufficient quantities of nitrous oxide to materially affect their overall GHG impacts.

SCR technology is now routinely fitted to most if not all heavy duty diesel-powered vehicles as part of the tailpipe NO<sub>x</sub> reduction strategy and in order to comply with Euro VI requirements. It

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<sup>13</sup> <http://content.tfl.gov.uk/in-service-emissions-performance-of-euro-6vi-vehicles.pdf>

injects a liquid-reductant agent through a special catalyst into the exhaust stream of a diesel engine. This agent, a type of urea solution with the trade name AdBlue, contains ammonia (NH<sub>3</sub>), and it sets off a chemical reaction that converts nitrogen oxides into nitrogen, water and small amounts of carbon dioxide (CO<sub>2</sub>). In sufficient quantities, the mixing of this ammonia with oxides of nitrogen can also lead to nitrous oxide production. Nitrous Oxide has a 100-year GWP of 298 (current GHG reporting guidelines), an order of magnitude greater than methane<sup>14</sup>.

The only published source of test data available was from testing of a Euro VI diesel-powered bus, as part of LowCVP's Low Emission Bus (LEB) certification scheme<sup>15</sup>. Under this testing process (chassis-dyno using a bus duty cycle consisting of rural, Outer London and Inner London phases), a 19t gross weight, double-deck, Euro VI diesel-hybrid bus, with SCR, was found to emit between 120 mg/km and 168 mg/km of nitrous oxide, depending on the phase. These figures increased the overall tailpipe GHG impact by between 4% and 8% (over and above the CO<sub>2</sub> only emissions, there being no methane emissions). The same engine in a single-deck, 19t Euro VI diesel-hybrid emitted between 89 mg/km and 152 mg/km of nitrous oxide, giving a GHG increase of between 3% and 8%, again depending on the particular test phase. A similarly sized dedicated gas bus, under the same test conditions, emitted no nitrous oxide (or methane).

Other (unpublished and confidential) evidence provided by a stakeholder indicated that their testing (also of bus engines including retrofit systems), had shown nitrous oxide emissions providing for up to a 10% increase in GHG emissions from SCR-equipped buses. Their testing also indicates that non-SCR equipped vehicles (Euro V and earlier) emit very low levels of nitrous oxide (< 10 mg/km).

The available evidence, albeit for bus engines operating to bus duty cycles, thus indicated that nitrous oxide emissions from Euro VI diesel trucks may add of the order of 5 – 10% to their overall GHG impacts. This has potentially significant implications for freight carbon reduction strategies and greenhouse gas reporting, which are beyond the scope of this study, but also has the potential to quite significantly increase the overall GHG savings available from gas-powered vehicles.

Although constrained by available time and budget, a limited programme of further testing (using Millbrook's chassis dynamometer and the World Harmonized Vehicle Cycle (WHVC) for the heavy vehicles or the World Light Duty Test Cycle (WLTC) for a small van) was commissioned to obtain additional data on the nitrous oxide issue, specifically from commercial vehicles operating to freight-relevant duty cycles.

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<sup>14</sup> The latest scientific evidence, described in the IPCC 5<sup>th</sup> Assessment Report (Synthesis Report, 2015) recommends a 100-year GWP of 265 for N<sub>2</sub>O and 28 for CH<sub>4</sub>, but these figures have not yet been officially adopted for reporting purposes.

<sup>15</sup> <http://www.lowcvp.org.uk/initiatives/leb/LEBCertificates.htm>

### 3.3 Test cycles

For the larger HGVs in the test programme (18t gross vehicle weight and over), the three test cycles already developed as part of the LowCVP retrofit technologies accreditation scheme were used:

- long haul (simulating predominantly motorway journeys),
- regional delivery (rural journeys)
- urban delivery (town centre/urban journeys).

For the smaller vehicles (up to 7.5t) and in order to provide a better match to TfL’s LoCITY work, the consensus view from stakeholders was to develop a fourth, city-centre delivery cycle to simulate heavily congested, city delivery operations. Between three and five repeat runs of each cycle were made for each vehicle tested to ensure appropriate repeatability and statistical validity of the (averaged) overall results.

A detailed discussion on the development of the original three cycles is beyond the scope of this report, but in brief they have been designed to follow in principle the long haul, regional delivery and urban delivery cycles being developed by the European Commission as part of the VECTO tool<sup>16</sup>. They use the correlation characteristics of the Kinetic Intensity (KI) cycle parameter, modified slightly to reflect UK traffic conditions (felt by stakeholders to be generally somewhat more “intensive”, that is with lower average speeds and more transient conditions associated with congested roads). The cycles developed, and used for this test programme, thus have slightly higher KI’s than the current VECTO cycles (as of 2015), as shown in Table 1. The Table also shows the average speed and kinetic intensity felt by the programme steering group to be most appropriate for the fourth, city-centre delivery cycle. The fuel consumptions shown in the Table for the original three cycles are derived from actual testing of such a vehicle on each cycle during development of the accreditation scheme procedures.

**Table 1. Main test cycle parameters**

	Long Haul	Regional Delivery	Urban Delivery	City-Centre Delivery
<b>Average speed (km/h)</b>	> 70	50 - 60	30 - 45	15 - 25
<b>Kinetic Intensity (per km)</b> (equivalent VECTO cycle figure in brackets)	0.14 – 0.20 (0.15)	0.24 – 0.36 (0.26)	0.70 – 1.00 (0.69)	2.60 – 3.00 (N/A)
<b>Fuel consumption of 18t rigid 70% payload (l/100km)</b>	22 - 27	26 - 31	29 - 35	

<sup>16</sup> Likely to be used for future measurement, reporting and regulation of heavy duty vehicle CO<sub>2</sub> emissions in the EU.

## 4 Test results

In total, four dedicated gas vehicles and their four diesel equivalent vehicles, and three dual fuel aftermarket conversion vehicles have been tested as part of the gas vehicle programme. The basic split was that the dedicated gas vehicles and their diesel equivalents were tested at Millbrook, while the dual fuel vehicles were tested by Horiba-Mira Ltd. Table 2 shows the overall test matrix.

One of the objectives of the test programme was to allow DfT to set the results of the Low Carbon Truck Trials (LCTT) in their wider GHG context. At the time of drafting, the full results from the LCTT were unpublished, but a draft of the final report was made available for review during the drafting of this report.

**Table 2. The gas vehicle test matrix**

Vehicle Code	Technology	Euro Level	Configuration	Payload	Tested Weight
Dedi01	OEM Dedicated Natural Gas (340 hp vs 320 hp comparator)	Euro VI	40t, 2+3 artic	15t	30t
Dedi02	OEM Dedicated Natural Gas (330 hp vs 460 hp comparator)	Euro VI	40t, 2+3 artic	15t	30t
Dedi03	OEM Dedicated Natural Gas (280 hp vs 250 hp comparator)	Euro VI	18t, 2 axle rigid	3t	15t
Dedi04	OEM Dedicated Natural Gas (140 hp vs 170 hp comparator)	Euro VI	7t, 2 axle van	1t	3.5t
Dual01	Aftermarket Dual Fuel Conversion (Diesel & Natural Gas)	Euro VI	44t, 3+3 artic	20t	36t
Dual02	Aftermarket Dual Fuel Conversion (Diesel & Natural Gas)	Euro V	44t, 3+3 artic	20t	34t
Dual03	Aftermarket Dual Fuel Conversion (Diesel & LPG)	Euro VI	44t, 3+3 artic	20t	36t

The following sections summarize the results from the testing programme. For brevity, the results presented from all the runs for each vehicle, on each test cycle, have been averaged. A more detailed set of results, from all the individual test runs and for all the vehicles tested, is available from the LowCVP website.

### 4.1 Greenhouse gas emissions

Table 3 shows the average emissions results, in g/km, for each vehicle, against the appropriate diesel/diesel-only mode equivalent, for each test cycle. For completeness, the 7t van (Dedi04) was tested in all four cycles to allow full comparison with the other (heavier) gas vehicles. Its diesel comparator, however, was not available for long enough to conduct a full programme of track tests, only the chassis-dyno tests.

For simplicity, for the natural gas vehicles and their diesel comparators, all measured THC is treated as methane in the calculations of CO<sub>2</sub> equivalent emissions, using a 100-year Global Warming Potential (GWP) for methane of 25, in accordance with current GHG reporting

practices<sup>17</sup>. In reality, the diesel comparator vehicle THC emissions will not be methane and for absolute precision should be subtracted from the test vehicle measurements so that only the increase in THC emissions is treated as methane. In practice, however, the THC emissions from the diesel comparator vehicles were found to be so low that there would be no material difference between these two approaches.

**Table 3. Greenhouse gas results for gas-fuelled vehicles (CO<sub>2</sub> & CH<sub>4</sub>)**

Vehicle Code	Cycle	Test vehicle emissions (g/km)			Diesel comparator emissions (g/km)			Overall GHG saving
		CO <sub>2</sub>	THC	CO <sub>2e</sub>	CO <sub>2</sub>	THC	CO <sub>2e</sub>	
Dedi01	UD	1,401	0.03	1,402	1,255	0.01	1,255	-12%
	RD	1,011	0.12	1,014	949	0.01	949	-7%
	LH	955	0.53	968	845	0.01	845	-15%
Dedi02	UD	1,212	0.09	1,215	1,317	0.01	1,317	8%
	RD	1,048	0.06	1,049	1,134	0.00	1,134	7%
	LH	1,000	0.24	1,006	1,051	0.02	1,051	4%
Dedi03	UD	806	0.02	807	845	0.00	845	5%
	RD	678	0.02	679	707	0.00	707	4%
	LH	649	0.02	650	654	0.00	654	1%
Dedi04 (Track)	CC	343	0.03	344	Vehicle not available for track testing			
	UD	225	0.02	226				
	RD	236	0.02	237				
	LH	225	0.01	226				
Dedi04* (Dyno)	CC#	331	0.02	331	294	0.00	299	-11%
	UD	250	0.01	250	227	0.00	229	-9%
	RD	235	0.01	235	229	0.00	233	-1%
	LH	199	0.01	199	213	0.00	217	8%
Dual01	UD	1,678	13.89	2,025	1,709	0.02	1,710	-18%
	RD	1,256	12.58	1,570	1,292	0.01	1,292	-22%
	LH	806	9.62	1,047	844	0.01	845	-24%
Dual02	UD	1,548	9.36	1,782	1,616	0.03	1,617	-10%
	RD	1,168	17.52	1,606	1,273	0.03	1,273	-26%
	LH	774	13.41	1,110	820	0.02	821	-35%
Dual03 <sup>!</sup>	UD	1,646	1.39	1,646	1,768	0.01	1,768	7%
	RD	1,403	2.10	1,403	1,387	0.01	1,387	-1%
	LH	882	1.83	882	890	0.01	890	1%

\* CO<sub>2e</sub> figures for this vehicle and comparator include any measured contributions from N<sub>2</sub>O.

! THC emissions from Dual03 are assumed to be unburnt LPG, not methane, and thus CO<sub>2</sub> and CO<sub>2e</sub> are identical for this vehicle.

# The most kinetically intense phase of the dyno test cycle used had a KI of 1.5, so this figure is used for the CC cycle here

#### 4.1.1 Greenhouse gas emissions, dedicated gas vehicles

For the dedicated natural gas vehicles, the GHG results are somewhat mixed. When comparing with a substantially higher-powered diesel vehicle (Dedi02), overall savings of 4-8% were measured, but in more like-for-like tests (Dedi01 and Dedi03), the savings were, at best, 5% and, at worst, the dedicated gas vehicle's emissions were some 15% higher than the diesel comparator. These results suggest that there are quite high efficiency losses under some

<sup>17</sup> At the time of writing, the latest scientific evidence, described in the IPCC 5<sup>th</sup> Assessment Report (Synthesis Report, 2015) recommends a 100-year GWP of 28 for methane, but this figure has not yet been officially adopted for GHG reporting.

operating conditions in moving from a compression ignition, conventional diesel engine to a spark-ignition one of similar power output (a topic discussed in more detail in section 4.3 of this report).

None of the dedicated gas vehicles tested were found to emit significant quantities of methane, i.e. there was, for these vehicles, little evidence of any methane slip. The highest levels of methane detected were from the two articulated vehicles when operating under the long haul test cycle, but even under these conditions the quantities involved were of the order of just 0.2 – 0.5 g/km, which on a CO<sub>2</sub> equivalence basis only increased the overall GHG emissions by about 1% compared to considering only the CO<sub>2</sub> emissions. The other dedicated gas vehicles, and these vehicles in all other test cycles, produced methane in quantities so low as to add less than 0.5% to their overall GHG impacts.

#### **4.1.2 Greenhouse gas emissions, dual fuel vehicles**

For the current generation dual-fuel vehicles operating on diesel and natural gas, levels of methane slip were found to be substantial under all test cycles (9 – 18 g/km). When considering only tailpipe CO<sub>2</sub> emissions, both these retrofit conversions (Dual01 to a Euro VI diesel and Dual02 to a Euro V) showed savings of between 4% and 11%, findings very much in line with those of the Low Carbon Truck Trial. When factoring in the measured methane slip, however, the overall GHG impacts of the dual-fuel vehicles rise by, on average, 26% for the Euro VI conversion and 37% for the older Euro V system, thus turning the CO<sub>2</sub> “savings” into overall GHG increases over the diesel-only baselines of around 10 – 35%.

The dual-fuel diesel and LPG retrofit conversion (of a Euro VI diesel tractor unit) also showed quite high levels of hydrocarbon (THC) emissions (1 – 2 g/km). These emissions are presumed unburnt fuel, in this case LPG, not methane, and thus do not contribute to the overall GHG impacts. This system generally achieved modest, but measurable, GHG savings. Across all three test cycles, the average measured savings were 2.3 %.

#### **4.1.3 Nitrous oxide emissions**

Results from the programme of work to measure nitrous oxide emissions are summarized in Table 4. Where multiple test runs were completed, the results shown are averaged.

These figures confirm that the non SCR-equipped vehicles exhibit low levels of nitrous oxide emissions. For the dedicated gas vehicle, there were no such emissions, though there were small quantities of methane slip, in line with the test track measurements described above (0.01 – 0.02 g/km). For the non-SCR diesel vehicles, N<sub>2</sub>O emissions of around 1 - 10 mg/km were measured, sufficient to increase the overall GHG impacts of such vehicles by around 0.4 – 0.8%.

The two SCR-equipped vehicles tested show higher levels of N<sub>2</sub>O emissions than the non-SCR versions, at levels high enough to add about 1 – 2% to the overall GHG impacts. While this is encouraging to some extent, in that such impacts are about one quarter of those suggested by

the bus evidence described above, it should be noted that this is just two vehicles and their performance may not be representative of other SCR-equipped vehicles, particularly those with larger engines or those with differing NOx reduction strategies.

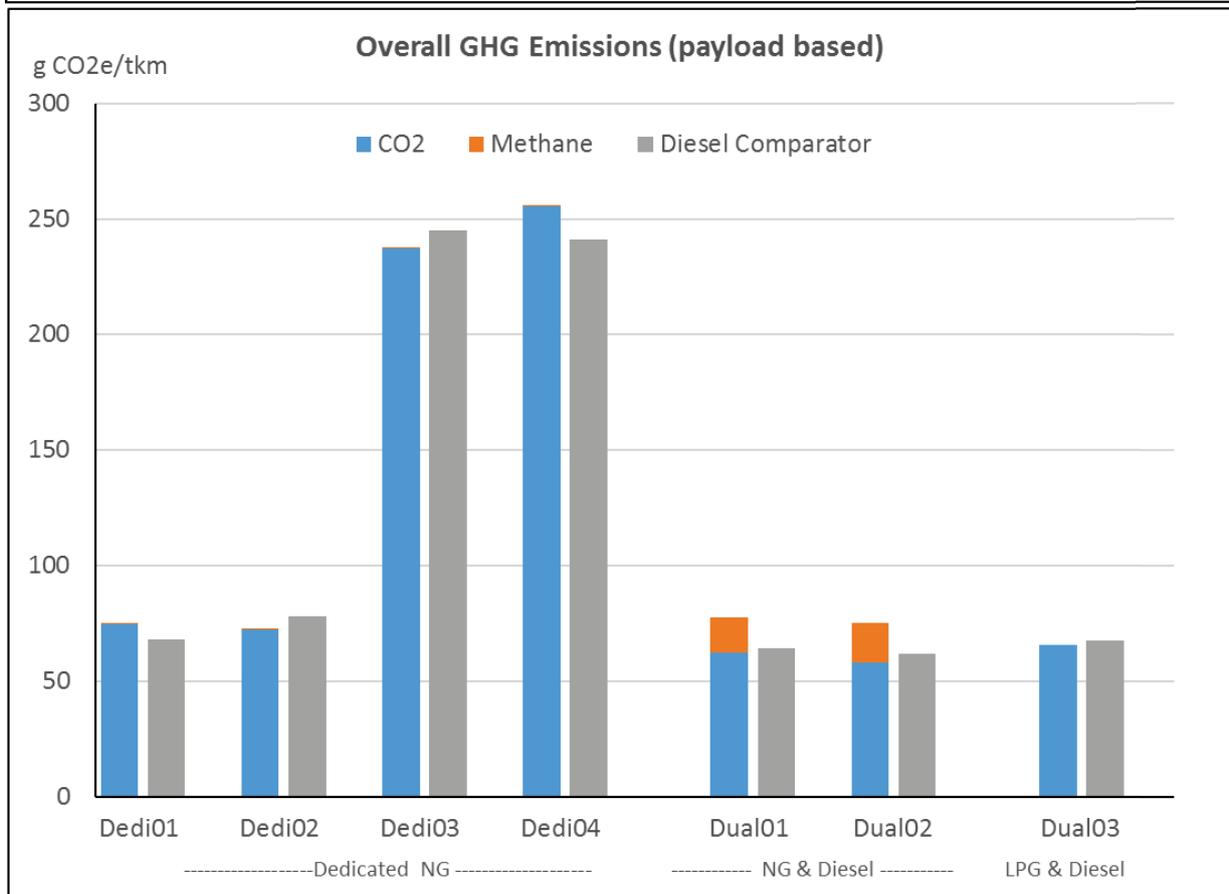
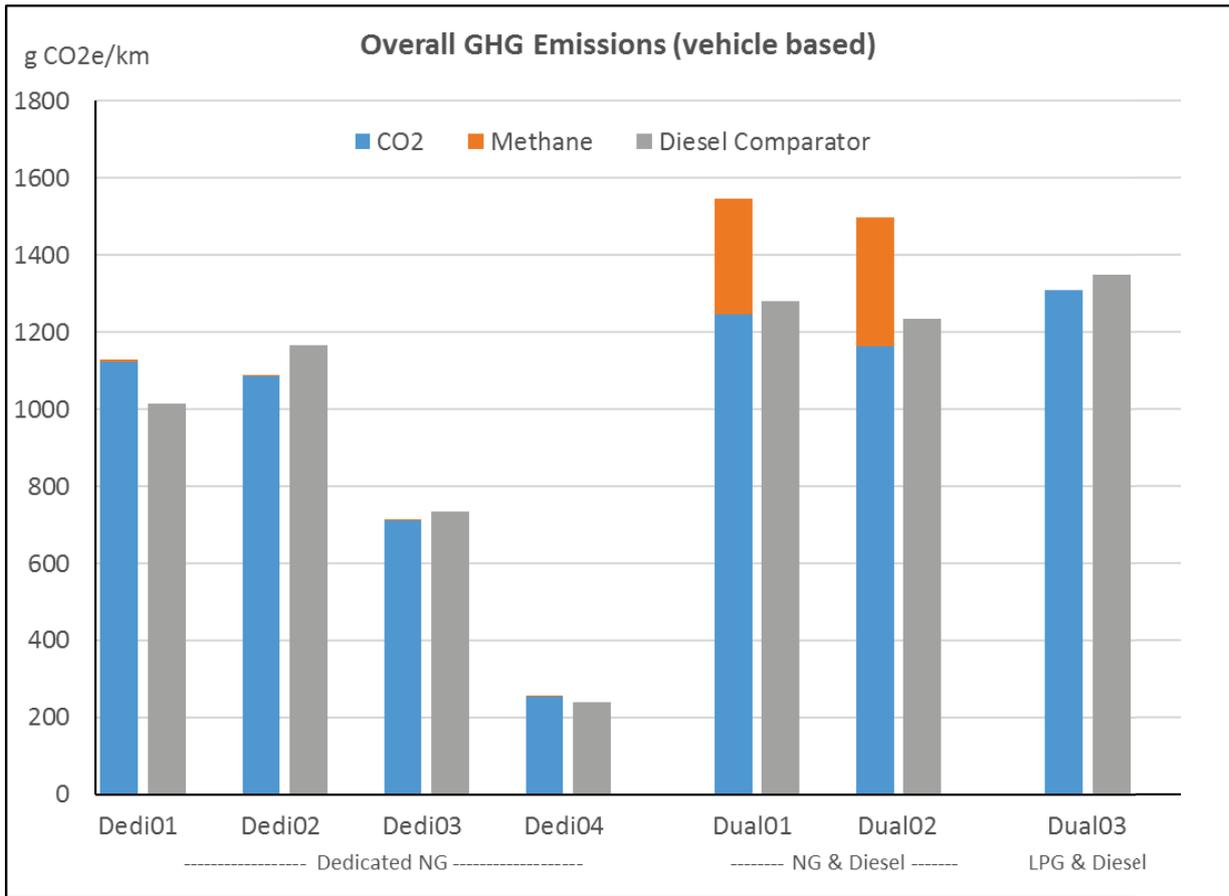
**Table 4. Measurements of Nitrous Oxide emissions**

Vehicle (Cycle)	Technology	Phase	N2O (mg/km)	CH4 (mg/km)	CO2 (g/km)	% increase in GHG from N2O
<b>7t Large Van (WHVC)</b>	Euro VI Dedicated Gas (CNG)	Urban	0	17	328	0%
		Suburban	0	7	220	0%
		Motorway	0	8	192	0%
		<b>Combined</b>	<b>0</b>	<b>10</b>	<b>236</b>	<b>0%</b>
<b>7t Large Van (WHVC)</b>	Euro V Diesel (not SCR-equipped)	Urban	4	0	254	0.5%
		Suburban	2	0	174	0.3%
		Motorway	1	0	183	0.2%
		<b>Combined</b>	<b>3</b>	<b>0</b>	<b>199</b>	<b>0.4%</b>
<b>2t Small Van (WLTC)</b>	Euro 6 Diesel (not SCR-equipped)	Low speed	10	0	182	1.6%
		Medium speed	7	0	150	1.4%
		High speed	3	0	152	0.6%
		Extra High speed	3	0	222	0.4%
		<b>Combined</b>	<b>5</b>	<b>0</b>	<b>181</b>	<b>0.8%</b>
<b>7.5t Truck (WHVC)</b>	Euro VI Diesel (with SCR)	Urban	20	0	605	1.0%
		Suburban	12	0	451	0.8%
		Motorway	35	0	458	2.3%
		<b>Combined</b>	<b>24</b>	<b>0</b>	<b>495</b>	<b>1.4%</b>
<b>7t Large Van (WHVC)</b>	Euro VI Diesel (with SCR)	Urban	17	0	292	1.7%
		Suburban	8	0	207	1.2%
		Motorway	14	0	208	2.0%
		<b>Combined</b>	<b>14</b>	<b>0</b>	<b>230</b>	<b>1.8%</b>

#### 4.1.4 Overall GHG emissions summary

Graphical summaries of the overall GHG emissions from all the tested vehicles are shown in Figure 2. For ease of presentation, the results from all test cycles for each vehicle (shown in Table 3) have been averaged, and the contribution, if any, from methane slip converted into g CO<sub>2</sub>e. The small contribution from N<sub>2</sub>O emissions measured during the dyno testing of the diesel comparator for Dedi04 is included in the results for that vehicle, but not separately identified.

The chart on the top presents the averaged data on a vehicle basis, in grams of CO<sub>2</sub> equivalent per vehicle kilometre travelled. The lower chart normalizes this same data by payload carried, in grams of CO<sub>2</sub> equivalent per tonne-kilometre of goods moved.



**Figure 2. Overall GHG emissions from tested vehicles**

## 4.2 Pollutant emissions

The measured average emissions of Carbon Monoxide (CO), Oxides of Nitrogen (NO<sub>x</sub>) and, where available, primary Nitrogen Dioxide (NO<sub>2</sub>) are shown in Table 5. Aside from particulate emissions, which for the reasons explained above were not measured during this (track-based) test programme, the pollutants of greatest current concern are the oxides of Nitrogen (NO<sub>x</sub>), and, of those, Nitrogen Dioxide (NO<sub>2</sub>) especially.

**Table 5. Pollutant emission results for gas-fuelled vehicles**

Vehicle Code	Cycle	Test vehicle emissions (g/km)			Diesel comparator emissions (g/km)			NO <sub>x</sub> saving
		CO	NO <sub>x</sub>	NO <sub>2</sub>	CO	NO <sub>x</sub>	NO <sub>2</sub>	
Dedi01	UD	0.61	0.14	0.05	0.57	0.20	0.08	0.06
	RD	0.54	0.09	0.02	0.26	0.13	0.08	0.05
	LH	0.85	0.04	0.02	0.13	0.11	0.02	0.08
Dedi02	UD	4.32	0.12	0.03	1.38	0.33	0.14	0.21
	RD	2.37	0.11	0.03	1.69	0.22	0.08	0.11
	LH	2.35	0.07	0.03	1.15	0.22	0.15	0.15
Dedi03	UD	0.76	0.16	0.02	0.60	0.38	0.01	0.22
	RD	0.47	0.12	0.01	0.40	0.19	0.00	0.07
	LH	0.45	0.21	0.02	0.33	0.14	0.02	-0.07
Dedi04 (Track)	CC	0.05	0.42	0.02	Vehicle not available for track testing			
	UD	0.10	0.38	0.01				
	RD	0.08	0.24	0.01				
	LH	0.08	0.13	0.00				
Dedi04 (Dyno)	CC/UD (Urban)	0.02	0.32	0.01	0.00	0.32	0.10	0.00
	RD (Suburban)	0.00	0.17	0.00	0.00	0.27	0.13	0.10
	LH (Motorway)	0.01	0.07	0.00	0.00	0.20	0.15	0.13
Dual01	UD	2.02	0.21	-	2.41	0.22	-	0.01
	RD	1.43	0.34	-	2.67	0.17	-	-0.17
	LH	0.50	1.07	-	1.58	0.11	-	-0.96
Dual02	UD	22.57	14.87	-	9.54	16.86	-	1.99
	RD	18.11	12.62	-	3.98	15.67	-	3.05
	LH	12.37	8.23	-	1.92	10.85	-	2.62
Dual03	UD	6.08	0.12	-	4.36	0.22	-	0.10
	RD	3.98	0.03	-	0.63	0.04	-	0.01
	LH	2.51	0.16	-	0.88	0.17	-	0.01

### 4.2.1 Pollutant emissions, dedicated gas vehicles

The Euro VI dedicated gas vehicles tested produced, on average, NO<sub>x</sub> emissions of about 135 mg/km over the three/four cycles, while the Euro VI diesel comparators produced, on average, about 230 mg/km. When comparing the in-cycle average NO<sub>x</sub> emissions, the dedicated gas vehicles produced lower levels of NO<sub>x</sub> emissions than the diesel comparators in all but one case (Dedi03 in the long haul cycle). Testing for statistical significance using the one-tailed, paired t-test, at the 95% confidence level, these data are sufficient to conclude that Euro VI dedicated gas vehicles emit lower levels of NO<sub>x</sub> than their diesel counterparts. The same is true for NO<sub>2</sub> emissions with, in this case, the gas vehicles producing about 20 mg/km on average, which is less than one-third of the 78 mg/km produced, on average, by the diesel comparators.

Emissions of carbon monoxide, however, were typically higher for the dedicated gas vehicles than their diesel equivalents, by approximately 0.5 g/km on average. Emissions of hydro-carbons (THC, unburnt fuel) were also higher, as discussed in the GHG results section.

Although not measured directly during the track-based programme, the manufacturers of the four tested dedicated gas vehicles did provide particulate emissions figures based on homologation approvals for their vehicles, and the diesel equivalents used in the test programme. These figures confirm the suggestion that particulate emissions are low from both diesel and dedicated gas vehicles, with the gas vehicles producing around 1 - 3 mg/kWh and the diesel variants 2 – 6 mg/kWh. The Euro VI limit value is 10 mg/kWh. The dyno testing used to measure nitrous oxide emissions also recorded particulate mass emissions, with figures of around 1 mg/km achieved by the dedicated gas vehicle and 1 – 4 mg/km by the Euro V or VI diesel vehicles tested (combined results, WHVC cycle).

#### **4.2.2 Pollutant emissions, dual fuel vehicles**

For the dual fuel, diesel and natural gas conversion of a Euro VI vehicle (Dual01), the NO<sub>x</sub> emissions were, on average, greater in dual-fuel mode (540 mg/km on average) than with the same vehicle operating in diesel-only mode (170 mg/km), but the CO levels were lower. For the diesel and LPG conversion of a Euro VI vehicle (Dual03), the NO<sub>x</sub> emissions were lower (100 mg/km on average) than when in diesel-only mode (140 mg/km) but the CO emissions were higher. These differences, as well as the THC (unburnt gas) emissions described in the GHG section, suggest that current applications of retrofit dual-fuel technologies do involve some compromises with regard to the overall ability of the vehicles' exhaust after-treatment systems to fully mitigate emissions of all the regulated pollutants.

The after-market conversion of a Euro V vehicle (Dual02) produced statistically significantly lower NO<sub>x</sub> emissions in dual-fuel mode (12 g/km on average) than when operated in diesel-only mode (14.5 g/km), but emissions of CO were much higher. These data indicate first, that such compromises in overall pollutant emissions control seem to have been necessary at the more basic Euro V levels too and, second, that the move to Euro VI has, for these diesel vehicles, been effective in cutting overall NO<sub>x</sub> emissions by over 98% from Euro V levels. The results described above suggest that a further move from Euro VI diesel vehicles to Euro VI dedicated gas increases the magnitude of that reduction in NO<sub>x</sub> emissions to at least 99%.

### **4.3 Substitution rates and efficiency losses**

The draft report of the LCTT highlights clearly the links between tailpipe CO<sub>2</sub> emissions, energy substitution rates (ESR) and efficiency loss ( $\Delta\mu$ ). Minimizing efficiency losses and maximizing the substitution rates provides the greatest savings in CO<sub>2</sub> when displacing diesel for natural gas. To facilitate further comparison between the test data described above and the rates/efficiency losses discussed in the LCTT report, this section presents the calculated ESR and  $\Delta\mu$  values.

For all tests, diesel consumption was measured accurately using a fuel flow meter but such a robust method of measuring gas consumption does not currently exist. Instead, the Carbon Balance Method has been used to calculate fuel consumption. This works by adding up all the carbon molecule masses from the carbon-containing compounds captured by the PEMS equipment and using the known chemical properties of the fuel to calculate the weight of fuel consumed. It works on the basic premise that any carbon in the exhaust stream must have come from the original fuel, and be emitted as either as CO, CO<sub>2</sub> or THC (which is taken as a proxy for unburnt fuel). It is widely used by industry and for legislative test purposes.

The ESR and  $\Delta\mu$  values for all the test vehicles are shown in Table 6.

**Table 6. Substitution Rates and Efficiency Losses for gas-fuelled vehicles**

Vehicle Code	Cycle	Test vehicle fuel consumption (MJ/km)			Diesel comparator fuel consumption (MJ/km)	Energy Substitution Rate, ESR (%)	Efficiency Loss, $\Delta\mu$ (%)
		Diesel	Gas	Total			
Dedi01	UD		24.4	24.4	17.0	100%	43%
	RD		17.6	17.6	12.9	100%	37%
	LH		16.7	16.7	11.4	100%	46%
Dedi02	UD		21.2	21.2	17.8	100%	19%
	RD		18.3	18.3	15.4	100%	19%
	LH		17.5	17.5	14.3	100%	23%
Dedi03	UD		14.0	14.0	11.5	100%	22%
	RD		11.8	11.8	9.6	100%	23%
	LH		11.3	11.3	8.9	100%	28%
Dedi04 (Track)	CC		6.0	6.0	Vehicle not available for track testing		
	UD		3.9	3.9			
	RD		4.1	4.1			
	LH		3.9	3.9			
Dedi04 (Dyno)	CC		5.8	5.8	4.0	100%	45%
	UD		4.3	4.3	3.1	100%	42%
	RD		4.1	4.1	3.1	100%	32%
	LH		3.5	3.5	2.9	100%	20%
Dual01	UD	18.7	5.9	24.6	23.2	24%	6%
	RD	13.6	5.0	18.6	17.5	27%	6%
	LH	8.3	3.9	12.1	11.5	32%	6%
Dual02	UD	16.5	6.8	23.3	22.1	29%	5%
	RD	11.1	7.3	18.5	17.3	40%	7%
	LH	6.6	6.0	12.6	11.1	47%	13%
Dual03	UD	21.3	1.3	22.6	24.0	6%	-6%
	RD	16.2	3.3	19.5	18.8	17%	4%
	LH	10.1	2.2	12.3	12.1	18%	2%

ESR is the ratio of the energy content of the gas consumed to the energy content of the diesel and gas combined. For the dedicated gas vehicles, it is 100% (because there is no contribution from diesel), but for the dual fuel vehicles, it typically varies between about 10% and 40%,

depending on the technology and test cycle. The natural gas dual fuel vehicles had ESR values in the range 24 – 47%, which compares very closely to the range of 25 – 52% found by LCTT.

$\Delta\mu$  is the increase in the energy content of the fuel(s) consumed by the dedicated gas or dual-fuel vehicles over the diesel comparator case, as a proportion of the diesel comparator case. If the efficiency loss is zero, the energy content of the gas consumed is exactly the same as the energy content of the diesel consumed by the comparator vehicle doing the same cycle (and carrying the same load). A  $\Delta\mu$  of x% implies that the test vehicle consumes fuel with an x% higher energy content than the diesel vehicle, to do the same work.

The dedicated gas vehicles show efficiency losses of typically in the range of 20 – 45%, which is very much in line with the LCTT findings for the (one make/model of) dedicated gas truck involved in those trials (24% efficiency loss against a relatively inefficient, higher-powered diesel comparator). The natural gas and diesel dual fuel vehicles, with their lower substitution rates and diesel combustion process, typically show lower efficiency losses; in the range 5 – 15% (also in agreement with the LCTT findings which estimated an average efficiency loss for such vehicles of 7% and an overall range of 0 – 25%). The dual fuel LPG-diesel vehicle has still lower substitution rates and correspondingly lower efficiency losses or, indeed, small efficiency gains, in the range -6 to +4 %.

## 5 Discussion

### 5.1 Greenhouse gas emissions

#### 5.1.1 *Dedicated gas vehicles*

The LCTT involved only six dedicated gas trucks (all Euro VI from the same manufacturer). The trial recorded an average efficiency loss of 24%, with the dedicated gas vehicles producing about 4% higher Tank-to-Wheel CO<sub>2</sub> emissions (calculated on a like-for-like 100% fossil diesel vs natural gas basis, ignoring any influences from blending with bio-methane). The single diesel comparator for these vehicles, however, was a Euro V vehicle with a larger, more powerful engine and different transmission system. This larger engine can be expected to be itself less efficient than a diesel engine with a lower power rating, so one could reasonably expect that if the comparison had been between the dedicated gas vehicles and a diesel vehicle with a less powerful engine (and closer match to the gas engine), the efficiency loss would be somewhat higher than the 24% recorded and the emissions increase would be higher than the 4% recorded.

In the HGV emissions testing programme reported on here, the two comparable dedicated gas articulated vehicles (Dedi01 and Dedi02) produced broadly similar results, in that on a near like-for-like comparison (Dedi01, similar engine size and transmission, and both Euro VI), the efficiency losses (c. 40%) negated any CO<sub>2</sub> savings, so overall GHG emissions from the dedicated gas vehicle were around 10% higher. When comparing with a much larger engine Euro VI diesel (Dedi02), the smaller (and thus inherently more efficient) dedicated gas engine, despite efficiency losses of some 20%, was able to produce lower CO<sub>2</sub> emissions than the diesel vehicle, by about 6% overall.

Both the LCTT and this test programme therefore indicate that current generation (Euro VI) dedicated gas vehicles, running on natural gas (rather than bio-methane), are likely to have broadly similar GHG impacts compared to Euro VI diesel equivalents, to within +/- 10%.

This test programme has, however, also shown that there is no appreciable methane slip from current generation dedicated gas vehicles. It has also started to build some evidence regarding emissions of nitrous oxide, which do not apply to dedicated gas vehicles, but may serve to increase the overall GHG impacts of Euro VI diesel vehicles by at least 2% and possibly by as much as 8% in some cases.

The LCTT results also highlight the potential for bio-methane to radically alter the relative GHG contributions. There, the dedicated gas vehicles were, on average, running with a 15% bio-methane blend of gas, which was sufficient to turn what would otherwise have been a reported 4% increase in CO<sub>2</sub> emissions (compared to the Euro V diesel comparator used) into a 10% emissions saving. Without any substantial risk of methane slip identified, the test programme has further confirmed the potential for substitution of natural gas with bio- (or other forms of non-fossil, renewable) methane to reduce GHG emissions.

### 5.1.2 Dual-fuel vehicles

The draft LCTT report indicates that when running on natural gas (and fossil diesel), the retrofit dual-fuel conversion systems (almost exclusively applied to Euro V vehicles) achieved tailpipe CO<sub>2</sub> emissions savings of, at best, 6% and, at worst, a CO<sub>2</sub> increase of about 5%. The exact savings or increases were found to depend on the particular technology, the gas substitution rate achieved and the levels of combustion efficiency loss. As the draft LCTT report acknowledges, however, these figures do not take into account any other GHG emissions, including those associated with methane slip.

Our own test programme confirms that methane slip was, and remains, a significant issue for trucks converted from diesel-only to dual-fuel operation. When considering only CO<sub>2</sub> emissions, both the retrofit conversions (Dual01 to a Euro VI diesel and Dual02 to a Euro V) showed savings of between 4% and 11%, findings very much in line with those of LCTT and with a high degree of agreement with the LCTT findings, too, in terms of substitution rates and efficiency losses. When factoring in the measured methane slip, however, the overall GHG impacts of the dual-fuel vehicles rise by, on average, 26% for the Euro VI conversion and 37% for the older Euro V system, thus turning the CO<sub>2</sub> “savings” into overall GHG increases over the diesel-only baselines of around 10 – 35%. At these levels of methane slip, very high blends of bio-methane (>50%) would be needed to achieve even GHG parity with equivalent diesel vehicles, let alone appreciable GHG reductions.

Work to develop methane-diesel, dual-fuel technologies with greatly reduced methane slip levels, both by retrofit companies and by OEMs, is ongoing and discussed in the following section of this report.

The dual fuel, diesel/LPG vehicle showed consistently low efficiency losses; indeed it achieved efficiency gains in some tests. Its substitution rates were a little lower than the diesel/natural gas dual fuel vehicles at around 15 – 20%. With no methane slip issues (although there was slippage of unburnt LPG), this vehicle returned overall GHG savings of up to 7%, and 2% on average.

## 5.2 Future technology developments

The test programme described above was inevitably constrained by the availability of technologies to test. The field of gas-powered heavy duty vehicle technologies is now a rapidly evolving one, with many new developments emerging. This section describes the results of some consultations with industry stakeholders to map out those developments and, in the absence of hard test data, assess their possible implications for emissions. The technologies are categorized into three groups: OEM dedicated gas technologies, OEM dual fuel technologies, and retrofit conversion technologies.

### 5.2.1 OEM dedicated gas technologies

The main developments here are focused on increasing the power outputs of dedicated gas engines, so that vehicles using those engines can more effectively compete in the market, particularly for the most common heavy, long haul applications characterized by 3+3 axle articulated vehicles operating at gross weights of up to 44t and with engines of around 450 hp maximum power output.

At the outset of the test programme, there were three OEMs active in the dedicated gas market in the UK, Iveco, Mercedes-Benz Trucks and Scania, but none had dedicated gas engines available with power outputs greater than approximately 340 hp. In the latter stages of the project (June 2016), Iveco officially launched a new, 400 hp articulated vehicle (Figure 3). Scania offer both 280 hp and 340 hp dedicated gas two and three axle rigid (Figure 4) and 4x2 articulated vehicles. Both companies are also developing > 400 hp dedicated gas engines, with expectations of market availability in 2018. At the time of drafting this report, Mercedes-Benz has not publicly announced any plans to expand its dedicated gas range beyond the 18t and 26t Econic vehicles already available in the UK direct from its factory.



**Figure 3. The latest OEM dedicated gas/methane vehicle, 400 hp (launched June 2016)**

The evidence gathered for the test programme, on various, relatively low-power dedicated gas engines, indicates that their overall GHG emissions performance, when operating on natural gas, and compared to equivalent fossil-diesel vehicles, is variable - between about 5% lower than diesel to around 10% greater. Factoring in possible (but as yet uncertain) emissions of nitrous oxide from the diesel vehicles, these figures may well be reversed (i.e. to between 10% lower and 5% higher). The main barrier restricting the GHG performance is the efficiency loss when moving from compression-ignition diesel engines to spark-ignition dedicated gas. While some marginal improvements in overall efficiency are likely as the new, higher-powered engines come

to market and other vehicle systems are optimized for dedicated gas engines, it seems unlikely that there will be a radical change in that basic issue. Further testing as and when such technologies become available would be needed to confirm the validity of this premise.

From a policy-making perspective, it seems reasonable to assume, in the absence of any further evidence to the contrary, that a shift in the market towards dedicated gas vehicles would be unlikely to dramatically reduce (or increase) overall road freight GHG emissions, if they operate on pure natural gas or with very low bio-methane blends (c. 5%). If bio-methane availability for road freight transport increases to allow for 10% blends or even higher (and bio-diesel blending/availability does not increase proportionately), then such vehicles could start to make a meaningful contribution to carbon budgets and overall carbon emissions reduction targets, relative to diesel HGVs.



*Figure 4. A currently available OEM dedicated gas rigid vehicle*

### **5.2.2 OEM dual-fuel technologies**

The LCTT involved one OEM dual-fuel technology, as developed by Volvo and applied to Euro V vehicles. The draft LCTT report indicates that this system achieved both low/no efficiency losses and high gas substitution rates (of almost 50%), and overall CO<sub>2</sub> savings of around 10% compared to an equivalent diesel vehicle (or the same vehicle running in diesel-only mode).

This system was not tested as part of the current programme as it is no longer available, so there is no direct evidence on any methane slip. As an OEM system, however, one could reasonably expect little or no methane slip, through a combination of optimized combustion efficiency and effective methane catalysis. The LCTT data also indicates that there was no efficiency loss with this system, a further indication of low methane slip – as high methane slip would inevitably

mean high efficiency losses, too, through not combusting the methane and thus not extracting any usable energy out of it as it passes through the engine.

Volvo are now developing a new dual-fuel system, known as High Pressure Direct Injection (HPDI). Their lead technology partner in this endeavour is Westport. The HPDI system promises to be a radical departure from the previous technology, in that it will achieve very high gas substitution rates (over 90%) because only a small amount of diesel fuel will be needed, simply to provide the “spark” to ignite the gas. By using the inherently more efficient compression-ignition cycle to combust the diesel, and thus provide the necessary flame to ignite the gas, the system should also achieve low or zero efficiency losses. By combusting predominantly gas, the system is also being designed to achieve very low levels of particulate and engine-out NOx emissions, reducing the need for complex exhaust after-treatment systems, but implying that the system will not be able to run in “diesel-only” mode. Volvo currently expect the HPDI system to be available towards the end of 2017.

### **5.2.3**      *Retrofit dual-fuel conversions*

This test programme has confirmed the indications based on earlier research that retrofit conversions of Euro V diesel vehicles to dual-fuel, diesel and gas (methane) operation are prone to high levels of methane slip. Across all the test cycles, these levels have been found to be sufficiently high to turn what would otherwise be modest CO<sub>2</sub> savings (if running on natural gas) into overall GHG emissions increases of around 30-40%. The test programme has further indicated that the only currently available conversion of a Euro VI vehicle also has a propensity to slip methane, typically in slightly lower quantities than the previous versions, but still enough to cause overall GHG increases of around 20%.

To appeal to environmentally conscientious fleet operators, the retrofit companies recognize that more needs to be done to address this issue. There are two main strategies to do so; improving the in-cylinder combustion of methane and raising the effectiveness of exhaust methane catalyst systems.

As part of the Integrated Delivery Programme (IDP12) funding, Innovate UK and OLEV have supported two projects to develop improved dual-fuel systems; Heavy Duty Dual Fuel Demonstrator (HDDFD) and Plasma Removal of Methane from Natural Gas Dual-Fuel Engines (PROMENADE)<sup>18</sup>.

The HDDFD project is a £3m, three year programme to “develop new Heavy Duty Dual-Fuel (DF) combustion and after-treatment technologies to achieve future European emissions compliance with reduced carbon footprint at acceptable cost. The main deliverable will be a demonstration of 23% source-to-wheel carbon reduction relative to current diesel truck operation” (according to the public description of the project). The partners include Clean Air Power Ltd (part of Vayon

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<sup>18</sup> Details at <https://www.gov.uk/government/publications/innovate-uk-funded-projects>

Group Ltd), Criterion Catalyst Company (part of Shell UK), MAHLE Powertrain Limited, Brunel University London and Loughborough University, with completion due in 2019.

The PROMENADE project is also due to finish in 2019 and is a £1.8m project to “demonstrate the use of non-thermal plasma, advanced combustion and control techniques and Additive Manufacturing to allow dual-fuel (Diesel-Natural Gas) to meet Euro Stage VI emissions standard while delivering considerable fuel economy benefits over conventional diesel engines”. Its partners include Johnson Matthey Plc, G-volution Plc, HiETA Technologies and University of Manchester.

One of the current retrofit technology companies (G-Volution) is planning to launch a new system for Euro VI vehicles before the end of 2016. This system will use their patented “Optimiser” technology, which intercepts the fuel injector control signals / fuel demand signals sent by the original diesel engine Electronic Control Unit (ECU). The control signals are then modified by the Optimiser to deliver a lower dose of diesel fuel to the engine and simultaneously dose precisely the amount of secondary fuel (natural gas or LPG) required to retain the original engine power output. Engine power output when the engine operates in dual-fuel mode is therefore the same as in diesel-only mode. G-Volution claim that their system allows full engine ECU functionality to be retained, including the emissions control system, and allowing for seamless integration with the vehicle’s transmission system, so NOx emissions should be no worse than the diesel-only condition and fuel economy and drivability are enhanced. By injecting more precisely-controlled quantities of gas into the combustion chambers, there is also the potential to reduce the propensity for methane slip, but this should be verified by independent testing as and when the technology becomes available.

Another retrofitter (Mercury Fuel Systems Ltd), who specialize in diesel-LPG systems, are further developing their system, particularly its software and engine mapping to reduce NOx emissions and emissions of unburnt LPG. They are also planning to extend the range of Euro VI makes and models of vehicles to which their system can be applied, including DAF, Scania and Mercedes-Benz, and to increase (in early 2017) the availability of bio-LPG to further improve the overall GHG impacts of their system. The system is relevant to other alternative fuels, including methane, methanol and hydrogen, and these represent further areas of technology development.

## 6 Conclusions & Recommendations

### 6.1 Conclusions

#### Methane & CO<sub>2</sub>

- The Euro VI dedicated gas vehicles tested through this programme exhibit very low levels of methane slip, typically adding less than 0.5% to the overall GHG impacts of those vehicles compared with the CO<sub>2</sub>-only case.
- Current generation (Euro VI) dedicated gas vehicles, running on natural gas (rather than bio-methane), are likely to have broadly similar GHG impacts compared to Euro VI diesel equivalents, to within +/- 10%.
- The only after-market Dual Fuel system currently available, converting a Euro VI diesel truck to diesel and natural gas operation, exhibited high levels of methane slip (sufficient to increase GHG emissions by c. 20%).
- An after-market Dual Fuel diesel and LPG system (conversion of Euro VI diesel) exhibited similarly modest GHG benefits to some of the dedicated gas vehicles tested (c. 5% savings), and although some slippage of hydro-carbons was evident, this is unburnt LPG, not methane or any other GHG. It should be noted that the system tested has since undergone a software update that may well reduce the levels of hydro-carbon emissions.
- The after-market dual fuel (Diesel/CNG) conversion of a Euro V vehicle exhibited high levels of methane slip (sufficient to increase GHG emissions by c. 20-30%).
- Stakeholders have indicated that effective catalysis of methane is possible, as is more effective in-cylinder methane combustion. Two current Innovate UK/OLEV-funded projects are developing new retrofit dual-fuel systems, finishing in 2019. At least one OEM is developing its own dual fuel (diesel-methane) system, with availability anticipated towards the end of 2017.

#### Nitrous Oxide

- The research has not yet been able to disprove the hypothesis that Euro VI diesel trucks typically emit quite high levels of N<sub>2</sub>O. Further evidence is needed to quantify this.
- The tests show that N<sub>2</sub>O emissions are very low for the dedicated gas vehicle and the two non-SCR equipped diesel vehicles tested, but higher for the two SCR equipped diesel vehicles tested (both ≤ 7.5t gw), sufficient to add 1 – 2% to those vehicles' overall GHG impacts.
- For light duty vehicles, other technologies are known to exist that can deal with NOx emissions without producing significant quantities of N<sub>2</sub>O, but SCR is the primary technology currently available for heavy-duty diesel vehicles to comply with Euro VI emissions standards.

## Air pollutants

- Euro VI dedicated gas vehicles emit lower levels of NO<sub>x</sub> emissions than their diesel counterparts. The same is true if only NO<sub>2</sub> emissions are considered. Emissions of carbon monoxide and hydro-carbons, however, were typically higher.
- The testing indicates that the transition to Euro VI has, for diesel heavy goods vehicles, been effective in cutting overall NO<sub>x</sub> emissions by over 98% when compared to Euro V vehicles. A further move from Euro VI diesel vehicles to Euro VI dedicated gas increases the magnitude of that reduction in NO<sub>x</sub> emissions to at least 99%.
- The dual fuel diesel and natural gas system retrofitted to a Euro VI diesel vehicle exhibited increases in average NO<sub>x</sub> emissions in dual-fuel mode compared to the same vehicle in diesel-only mode, but to values still comparable to Euro VI diesels and very much lower than Euro V values. THC emissions also increased, but CO emissions were lower. The dual fuel diesel and LPG system retrofitted to a Euro VI diesel vehicle produced lower NO<sub>x</sub> emissions in its dual fuel mode compared to its diesel-only mode, though emissions of other regulated pollutants (CO and THC) increased.
- The after-market dual fuel system fitted to the Euro V vehicle consistently reduced NO<sub>x</sub> emissions by between 2 and 3 g/km but levels remain at least one order of magnitude higher than all Euro VI vehicles (diesel, gas or dual fuel). Emissions of other regulated pollutants (CO and THC) increased.

## 6.2 Recommendations:

- This study has shown that dedicated gas commercial vehicles have potential to deliver significant GHG savings when a non-fossil, bio- or synthetic methane blend is used. DfT should therefore continue to support the development of gas vehicle infrastructure and gas-powered vehicles, particularly dedicated gas, while increasing the supply of low carbon/renewable methane as a sustainable transport fuel in order to realize these benefits.
- This study has highlighted the potential for GHG savings from dual fuel diesel/LPG conversions, and the role of bio-LPG. DfT should also, therefore, consider enhancing its support mechanisms for this sustainable transport fuel.
- DfT should fund further research into N<sub>2</sub>O emissions from Euro VI diesel vehicles > 7.5t gvw.
- DfT should continue to develop its evidence on GHG and AQ performance of emerging commercial vehicle technologies.

## Glossary

Euro 1 (2, 3, 4, 5, 6) - certified Euro Emission level (Chassis dyno method for cars and vans)

Euro I (II, III, IV, V, VI) – certified Euro emission level (Engine test method for bus and truck)

AQ – Air Quality

GHG – Greenhouse Gas

NO<sub>x</sub> - oxides of nitrogen (NO and NO<sub>2</sub>) (pollutant)

NO – nitric oxide (pollutant)

NO<sub>2</sub> - nitrogen dioxide (pollutant)

N<sub>2</sub>O – nitrous oxide (GHG)

PM - particulate mass (pollutant)

CO – carbon monoxide (pollutant)

CO<sub>2</sub> - carbon dioxide (GHG)

CH<sub>4</sub> – methane (GHG)

THC – Total Hydrocarbons (pollutant). Emissions measured at the tailpipe assumed to be unburnt fuel, i.e. methane in case of natural gas vehicles.

KI – Kinetic Intensity (the ratio of the characteristic acceleration to the square of the aerodynamic speed, most commonly expressed in units of per km or per mile). A drive cycle parameter found by previous research and LowCVP testing to have a strong linear correlation to vehicle fuel consumption, CO<sub>2</sub> and other emissions.

LCTT – Low Carbon Truck Trials

SCR - Selective Catalytic Reduction, a technology applied particularly to Euro VI vehicles to reduce tailpipe emissions of NO<sub>x</sub>.

DF – Dual Fuel. A vehicle that operates on a mixture of two different fuels, diesel and gas.

NG – Natural Gas, assumed to be made up of 100% methane

CNG - Compressed Natural Gas

LNG – Liquefied Natural Gas

LPG - Liquid Petroleum Gas

PEMS - Portable Emissions Monitoring System

OEM – Original Equipment Manufacturer

WHVC- World Harmonized Heavy Vehicle Test Cycle

WLTC – World Harmonized Light Vehicle Test Cycle

Gvw – Gross vehicle weight

DfT – Department for Transport

OLEV – Office for Low Emission Vehicles

TfL – Transport for London

## Annex 1: LowCVP Accreditation Scheme Test Procedure

For the track-based testing of vehicles, the procedures use essentially standard industry practices. These involve having two nominally identical vehicles, with one remaining unmodified and used as a control, e.g. for changes in atmospheric conditions, and the other being the test vehicle run first, in baseline configuration, unmodified and then again, with the technology under evaluation being fitted/operational. This 'back-to-back' test method leads to four data sets for each test cycle:

- i. Control vehicle – baseline
- ii. Control vehicle – testing
- iii. Test vehicle – baseline
- iv. Test vehicle – testing

One of the wider objectives of the LowCVP scheme is to ensure any testing is affordable to as wide a part of the technology supplier community as possible. For this reason, testing is limited to two days, with the “baseline” tests on Day 1, and the “testing” tests on Day 2. Days 1 and 2 would not necessarily follow concurrently, depending, for example, on weather suitability and time needed to fit the technology.

Where the nature of the aftermarket technology being evaluated prohibits its easy removal, or to do so would leave the vehicle in such a condition as to be unrepresentative of normal freight operations, an appropriate comparator vehicle shall be selected and used in place of the Control vehicle, with as far as reasonably practicable, otherwise identical specifications to the Test vehicle (e.g. tyres, lubricants, engine power, transmission ratios etc.).

This test procedure does not make specific provisions for testing the effects of auxiliary loads such as cab air conditioning systems or loading compartment refrigeration units. All such loads will be turned off during the tests, unless they affect the normal operation of the vehicle.

The intention is to test the vehicle in its normal road-going condition and operating strategy as far as reasonably practicable, within the constraints of the equipment and duty cycles. Any aspect of vehicle operation which needs to be modified for the test shall be discussed with the test centre and recorded in the test report.

The vehicles will be tested over a minimum of three duty cycles, simulating City Centre Delivery, Urban Delivery, Regional Delivery and Long Haul operations. The required cycle characteristics are defined.

For the test vehicle, carbon dioxide (CO<sub>2</sub>) and regulated emissions (Total Hydrocarbons, CO and NO<sub>x</sub>) shall be sampled over the entire cycle and the results presented as g/km, using PEMS equipment attached to the tailpipe.

The Control vehicle shall, as a minimum, be equipped with a fuel-flow meter to accurately determine any changes in fuel economy performance between the baseline and testing days.