Provision of HGV Emissions Testing

Final Report

Report for Department for Transport

RM4470-SB2925

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Executive summary

Project overview

This project has developed a test protocol for quantifying methane emissions from Heavy Goods Vehicles (HGVs) that use methane as a fuel. The scope of the test protocol includes both dedicated methane fuelled vehicles and diesel/methane dual fuelled vehicles. The protocol is equally applicable to Original Equipment (vehicle) Manufacturer (OEM), or after-market converted, vehicles, although its relevance to the former may be limited in the context of vehicles that have been type-approved.

The project was commissioned by the Department for Transport's (DfT) Freight Policy team because there is currently interest in using methane as a vehicle fuel. Its use has the potential to contribute to reducing greenhouse gas (GHG) emissions from the transport sector, whilst also reducing air pollutants from vehicles, thereby improving air quality. However, while gas-fuelled HGVs offer potential carbon dioxide (CO_2) savings compared to diesel vehicles, due to the lower carbon intensity of gas relative to diesel fuel, the reduction in CO_2 emissions can be somewhat off-set, or in extreme cases reversed, because of methane emissions. Sometimes referred to as "methane slip", this is unburned methane emitted from the tailpipe. Methane is a potent greenhouse gas with a 100 year global warming potential (GWP) of 28[1]. Recent work by Ricardo-AEA for DfT[2] estimated that, for a dual fuel vehicle operating at typical substitution rates, if 2% of the methane fuel passes through the engine, unburnt, with 98% combusted (i.e. if the level of methane slip was 2%), then this could completely negate the greenhouse gas savings offered by using methane as a vehicle fuel in place of diesel. There is currently a lack of data on the level of methane emissions from gas-fuelled HGVs, particularly under real-world driving conditions. This project's primary purposes were to provide the following deliverables:

1) A test protocol that will allow both the accurate measurement of methane emissions from HGVs and the change in their CO_2 emissions relative to a comparator diesel only fuelled vehicle so that changes in GHG emissions can be assessed for the methane fuelled vehicles relative to comparator diesel fuelled vehicles;
2) A report on pilot testing of vehicles/equipment; and
3) Recommendations for wider testing of vehicles and equipment.

The test protocol produced will facilitate the building of an evidence base on the level of methane consumption and emissions from gas-fuelled HGVs, particularly under real-world driving conditions. The project comprised:

- A desk based review of methane emissions from heavy goods vehicles and the principal aspects of a possible test protocol;
- The initial development of a draft test protocol;
- The testing of both a dedicated methane fuelled vehicle and a diesel/methane dual fuelled vehicle using both chassis dynamometer and track testing using the draft testing protocol;
- The holding of a stakeholder workshop that included vehicle OEM, after-market converters, fleet operators and organisations offering testing services to further assess the draft test protocol;
- The final refinement of the draft test protocol, together with recommendations and a summary of the vehicle testing undertaken, all presented in a final report (this report).

In the protocol being developed, the primary measurement is the change in GHG emissions of a methane fuelled vehicle relative to a conventional diesel comparator vehicle.

Therefore, two aspects need to measured, methane emissions and CO_2 emissions for both the methane fuelled vehicle and the comparator vehicle. A third greenhouse gas, nitrous oxide (N_2O), would, in an ideal world, also be measured, but has been excluded because it is not currently possible to measure it accurately using portable emissions measuring equipment and, in any case, it is likely to be emitted in very low (and similar) quantities from both diesel and gas-fuelled vehicles.

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[1] Global warming potentials are expressed in terms of being relative to an equivalent mass of CO2, over a fixed period of time. The 100 year GWP for methane is given as 28 in the 5th IPCC Assessment Report (See Box 3.2 in reference http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf . However, this was revised upwards relative to the 100 year GWP for methane of 25 as given in the 4th IPCC Assessment Report and the current value adopted by the UNFCCC for national emission reporting. In this study we use 28, the more recent figure.

[2] *Waste and Gaseous Fuels in Transport – Final Report*. Ricardo-AEA report for DfT, July 2014.

Given current interest in other (pollutant) emissions, this study has also considered opportunities to measure them, particularly NOx, in order to also allow comparisons to be made between diesel fuelled and gas fuelled vehicles from an air quality perspective.

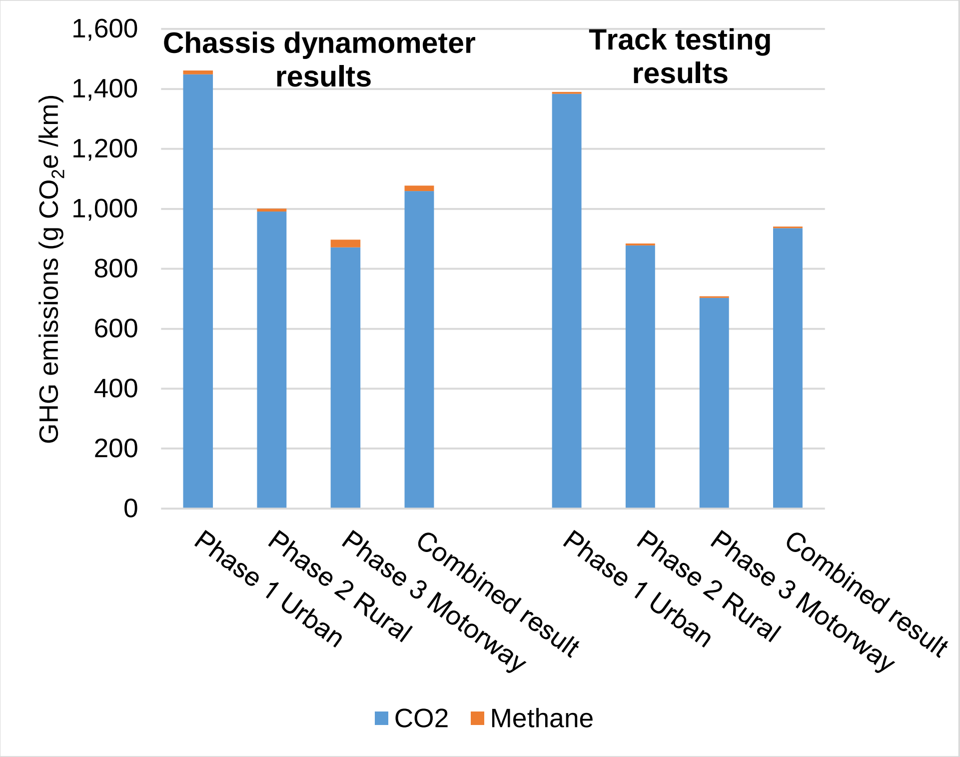
Overview of report structure

The structure of this report broadly follows the structure of the project outlined above. In brief:

Chapter 2	After an introductory chapter this covers most of the literature review, with some of the details being provided in Appendices 3 and 4.
Chapter 3	Describes a preliminary methane slip test protocol, which was based on evidence gathered during the literature review and formed the basis for the vehicle testing programme.
Chapter 4	Reports on results from the vehicle testing.
Chapter 5	Describes the stakeholder workshop that was held in March 2015, and some post-workshop discussions.
Chapter 6	Combines the evidence gathered from the literature, testing and stakeholders to detail the final recommended test protocol, the further testing appropriate to improve the evidence base on methane emissions from gas fuelled HGVs, and considers the potential extended use of the test protocol.

Vehicle testing

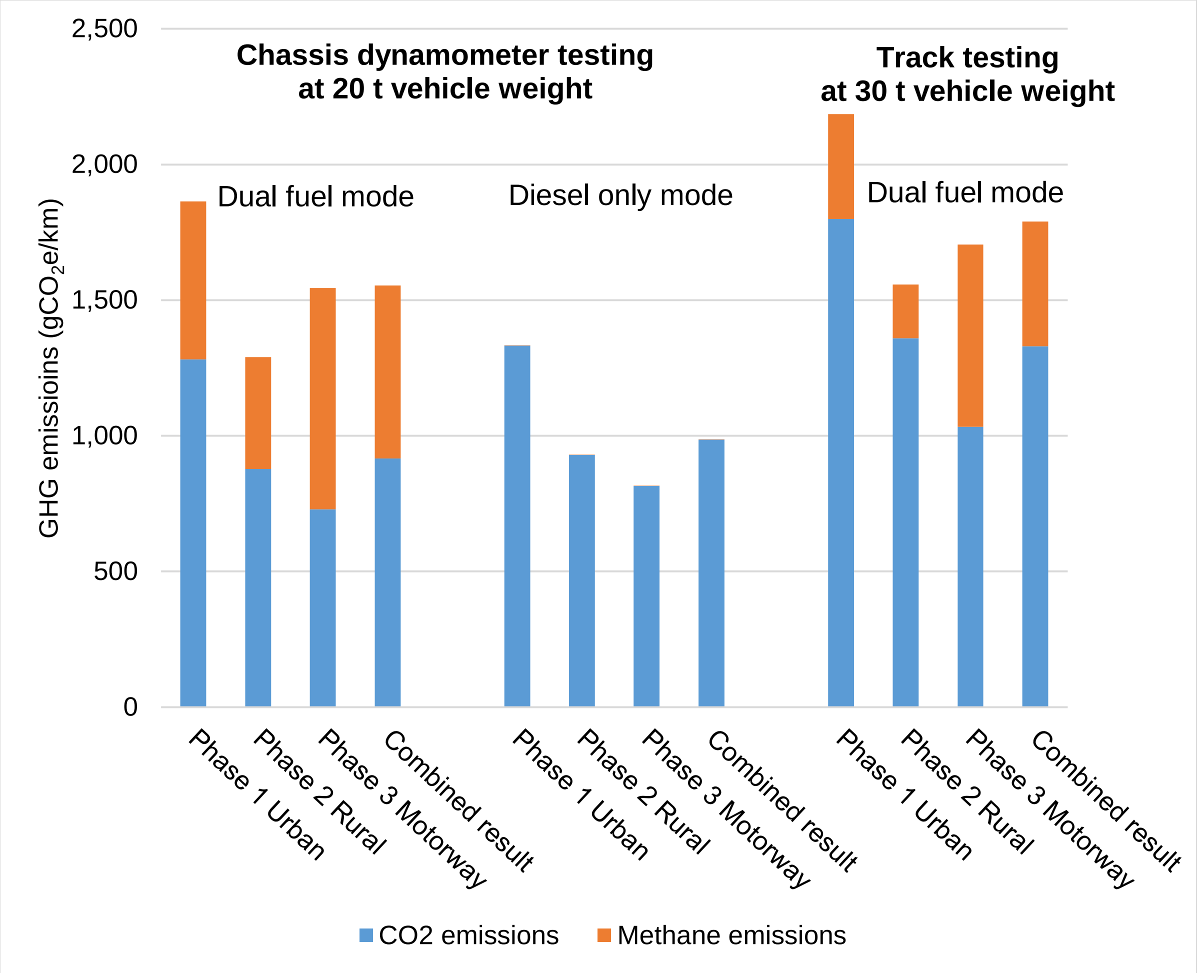
As noted above, both a Euro V dedicated methane fuelled vehicle and an aftermarket conversion Euro V diesel/methane dual fuelled vehicle were tested using both chassis dynamometer and track driving. When tested on the chassis dynamometer the diesel/methane dual fuelled vehicle was run in both its diesel only mode and in its dual fuel mode. The principal purposes of the vehicle testing were to assess the draft test protocol, to answer some questions raised, and to confirm some decisions made, during the desk based generation of the draft test protocol. The testing used the three components of the World Harmonised Vehicle Cycle (WHVC) which emulate urban, rural and motorway driving. Results of the combined (whole) cycle were also calculated. The greenhouse gas (GHG) emissions from these tests are summarised in the figure below for the dedicated methane vehicle.



These results show that the relative contribution of the methane emissions is small, despite its GWP of 28, although it is visible for the motorway phase of the cycle for the chassis dynamometer testing, and in the combined cycle.

This dedicated methane fuelled vehicle could not be run on diesel fuel to provide a diesel only comparator directly. However, an indication of the overall change in GHG emissions was obtained from an earlier research project undertaken by Coca-Cola Enterprises (CCE) and from standard emission factors. Both sources indicate that for this vehicle, whilst it has relatively low methane emissions, overall, relative to a diesel comparator, GHG emissions do increase, by around 12% over the full, combined cycle.

The analogous results for the methane/diesel dual fuel vehicle are shown below. The GHG emissions for the vehicle when tested on the chassis dynamometer, at the light load of 20 tonnes, and when the vehicle was tested on the track, at the heavier load of 30 tonnes are reported. Data from the vehicle operating with diesel only fuelling were measured for the chassis dynamometer testing but not for the track testing. In diesel only mode there is negligible GHG emissions contribution from the methane, whereas in dual fuel mode the methane emissions contribute markedly. The CO_2 emissions in diesel only mode are higher than in dual fuel mode. This is most easily seen for the combined result where in diesel only mode the CO_2 emissions are just below 1,000 g CO_2/km, whereas in dual fuel mode they are considerably below the 1,000 g/km line. Therefore, when operating in dual fuel mode there is a CO_2 saving, relative to the diesel comparator. However, for this vehicle the 22.7 g/km methane emissions lead to a further 638 gCO_2e/km emissions, i.e. the methane emissions cause the vehicle's overall GHG emissions to increase by 58%, despite the 7% reduction in CO_2 emissions.



It is emphasised that this study is not about testing specific vehicles but merely using them as a test bench for the development of a test protocol that can be used to gather evidence regarding changes in GHG emissions (and air quality pollutants) from methane fuelled vehicles. Therefore the important conclusion from the experimental study is that the protocol being developed does enable GHG and other emissions to be relatively accurately assessed, particularly for dual fuel vehicles where the emissions from the vehicle operating in diesel only mode can also be measured. The testing did also highlight the challenge of finding appropriate comparator vehicles for dedicated methane fuelled vehicles.

The recommended test protocol

The test protocol is summarised below.

The vehicle:

The test is applicable to both dedicated methane vehicles and dual fuel diesel/methane vehicles. It is recommended that whole vehicles should normally be tested with 50% to 60% payload weighting, as specified by EU legislation for checking the in-use compliance of heavy duty vehicles with air quality emissions limits (regulation 582/2011/EC). However, specifying a strict 50-60% payload range could impose an unnecessary constraint, e.g. on assessing how methane slip varies with payload, so it should be open to the test commissioner to define the appropriate payload.

Fuel:

A sample of the methane fuel used should be taken and analysed because fuel quality is a variable that has been shown to affect methane emissions, and currently there are a range of methane fuel qualities available. This requirement may be relaxed if it is found that either there is little variability in fuel quality, or little correlation with the amounts of methane expelled from HGVs during a typical drive cycle.

Track or road testing:

To meet the protocol's objectives, track testing is advocated.

Whilst road testing is potentially a valid alternative, advocated in the EC Directives for checking in use emissions, such testing has limited accuracy in determining changes in CO_2 emissions relative to the comparator vehicle. Therefore we consider that it is not appropriate for this test protocol.

Driving cycle:

The test protocol should reflect the real operation of the type of vehicles that will be tested. It is also vital that the driving cycles have similar average speeds and kinetic intensities to those used for the comparator vehicle. For a dual fuel vehicle this will most likely involve driving time-speed profiles that emulate urban, rural and motorway driving conditions with the vehicle in both dual fuel and diesel only modes. For a dedicated methane vehicle the choice of driving cycles needs to be directly comparable with the data available, or the testing undertaken, of the comparator vehicle.

Test procedure

A detailed test procedure has been drafted by Millbrook Proving Ground, building on their experience of measuring changes in CO_2 and other emissions between vehicles having different configurations.

The analysers used

The vehicle's emissions are to be analysed using Portable Emissions Monitoring Systems (PEMS) equipment (using equipment consistent with the PEMS specification in Annex II of Regulation 582/2011/EC). Methane should be measured (indirectly) using a flame ionisation detector (FID) which actually measures total hydrocarbon emissions, but these can be used as a suitable proxy for methane in methane fuelled vehicles. These requirements do not exclude any of the three main current types of PEMS systems available, and keep the protocol consistent with the type approval regulations.

The subsequent data analysis

The data analysis involves calculating the methane and CO_2 emissions for the vehicle under test when using methane fuel, and comparing these with the CO_2 emissions from a diesel-only comparator vehicle, assuming its methane emissions are negligible. This involves relatively standard data analysis, similar to that experienced in the PEMS testing of vehicles.

Other aspects of the test protocol

The test should be consistent with the PEMS specification in Annex II of Regulation 582/2011/EC. Specifically with regard to ambient conditions, engine coolant temperature, and exhaust temperatures.

Consideration of the output

A key aim of this project is to build an evidence base on methane slip from the measurement of the overall GHG emissions from methane powered vehicles (in terms of CO_2e and covering, as a minimum, tailpipe CO_2 and CH_4). It does not, of itself, set a pass/fail limit. Using data from the first annual report to the DfT on the "Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation", it was found that for the typical heavy goods vehicle operations emissions a methane slip of 2.6 g/km would just cancel the average reduction in CO_2 emissions. However, the methane emissions from the majority of vehicles were not characterised. In the context of the vehicle testing undertaken as part of this project, the dedicated Euro V vehicle tested gave methane slip levels comfortably below this value, while an after-market conversion system (again to a Euro V engine) gave significantly higher methane levels. The figure earlier in this Executive Summary shows how this changed a CO_2 reduction into a GHG increase.

Further recommendations

Recommendations for further testing to improve the evidence base on methane, overall GHG and other emissions from gas fuelled HGVs are:

- To restrict testing to categories where vehicles actually exist, e.g. current OEM dedicated and aftermarket dual fuel conversions. In the future it is anticipated this will extend to include OEM dual fuel vehicles;
- To focus on vehicles likely to be used commonly over the coming years, rather than the historic fleet. The latter are present in relatively modest numbers, a number of studies regarding their emissions have been made, and investing in finding the emissions from more of these vehicles in further detail is likely to have modest benefit; and
- To focus on the aftermarket dual fuel vehicle conversions because, unlike the OEM manufactured vehicles, these are unlikely to have been formally type approved and their GHG emissions are currently more uncertain. However OEM manufactured vehicles should still be tested in the same way as other types to build an evidence base on overall GHG savings.

It is noted that the different aftermarket dual fuel vehicle conversion companies have different fuelling strategies. Also the testing will occur in the context of rapidly developing technology, for which there is no clear way of accurately assessing the levels of methane emissions because there are too many interacting parameters. It is recommended that further testing of after-market produced dual fuel vehicles takes into account the following factors:

- Ideally vehicles should be tested from each of the companies who produce after-market dual fuel vehicles;
- Endeavour to engage with the companies who produce after-market dual fuel vehicles to better understand when technology changes occur, and the general ethos of the companies (e.g. in terms of research and their relationship with OEMs whose vehicles are being converted);
- Also, it is strongly recommended that DfT engineers engage with OEMs who produce dual fuel vehicles to better understand what factors the OEMs have found influence particularly durability(e.g. catalyst lifetime);
- A corollary to this would be to build up a database of the different companies who produce after-market dual fuel vehicles, the base vehicles they convert, and the numbers converted as a function of time; and
- Remain aware of the rapid pace at which innovation is occurring, particularly in the context of the base vehicles' technology changing with the introduction of Euro VI emissions standards. This means results obtained cannot be simply extrapolated to the previous and later generations of converted vehicles.

In addition to the immediate requirement of gathering an evidence base for methane fuelled heavy goods vehicles, the test protocol developed and described in this report can be extended to other methane fuelled heavy-duty vehicles.

The principal extensions would involve:

- **The driving cycle:** For buses or small delivery trucks the test cycle should be reviewed.
- **The selection of comparator vehicle CO_2 emissions:** For vehicles that cannot be tested in a diesel only fuelling mode, i.e. all dedicated methane vehicles and possibly some dual fuel

vehicles, an appropriate comparator vehicle would need to be identified, together with the obtaining of complementary CO_2 and other emissions data. This might involve the separate testing of a further (comparator) vehicle.

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Appendices

1 Introduction

1.1 Background to the study

There is currently considerable interest in using methane as a vehicle fuel. Its use can potentially contribute towards decarbonising the transport sector, whilst also reducing air pollutants from vehicles, thereby improving air quality. This is particularly the case for Heavy Goods Vehicles (HGVs) where there are fewer decarbonisation options available compared to other transport modes. In order to improve understanding and real world experience in using methane in HGVs, the Government is funding a number of projects using gas and dual-fuelled vehicles under the Low Carbon Truck Trial[3].

While gas-fuelled HGVs have the potential to offer CO_2 savings compared to diesel vehicles due to the lower carbon intensity of gas relative to diesel fuel, it is important to consider the overall change in greenhouse gas (GHG) emissions that occurs from tailpipe emissions of trucks that use methane. The reduction in CO_2 emissions can be somewhat off-set, or in extreme cases reversed, because of “methane slip”, i.e. unburned methane emitted from the tailpipe. Methane (chemical formula, CH_4) is a potent greenhouse gas – with a global warming potential of 28[4]. Recent work by Ricardo-AEA for the Department for Transport (DfT)[5] estimated that if the level of methane slip for dual-fuelled vehicles was 2% of the methane fuel passes through the engine, unburnt, with 98% combusted (i.e. if the level of methane slip for dual-fuelled vehicles was 2%), then this could completely negate the greenhouse gas savings offered by using methane as a vehicle fuel in place of diesel (Ricardo-AEA, 2014).

There is currently a lack of data on the level of methane emissions from gas-fuelled HGVs, particularly under real-world driving conditions. However, the body of evidence is increasing due to recent and ongoing vehicle test and measurement programmes, especially some of those connected to the Low Carbon Truck Trial.

It is possible to reduce emissions by using a methane catalyst, but the efficacy of such catalysts is also poorly understood. A clear understanding of methane emissions and how they may be minimised is important to ensure that the GHG emission savings potentially available from using this fuel can be fully achieved.

This project has been commissioned by DfT to increase the evidence base around methane slip from HGVs, specifically to quantify the amounts of methane expelled from HGVs during a typical drive cycle, why this occurs, how it can be minimised and what the impacts are on overall greenhouse gas emissions emitted by such vehicles during their use.

1.2 Study aims

The primary purpose of this study is to provide the following three deliverables:

1) A test protocol that will allow both the accurate measurement of methane emissions from HGVs and the change in their CO_2 emissions relative to a comparator diesel only fuelled vehicle so that changes in greenhouse gas emissions can be assessed for the methane fuelled vehicles relative to comparator diesel-fuelled vehicles;
2) A report on pilot testing of vehicles/equipment; and
3) Recommendations for wider testing of vehicles and equipment.

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[3] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/321248/low-carbon-truck-trial.pdf

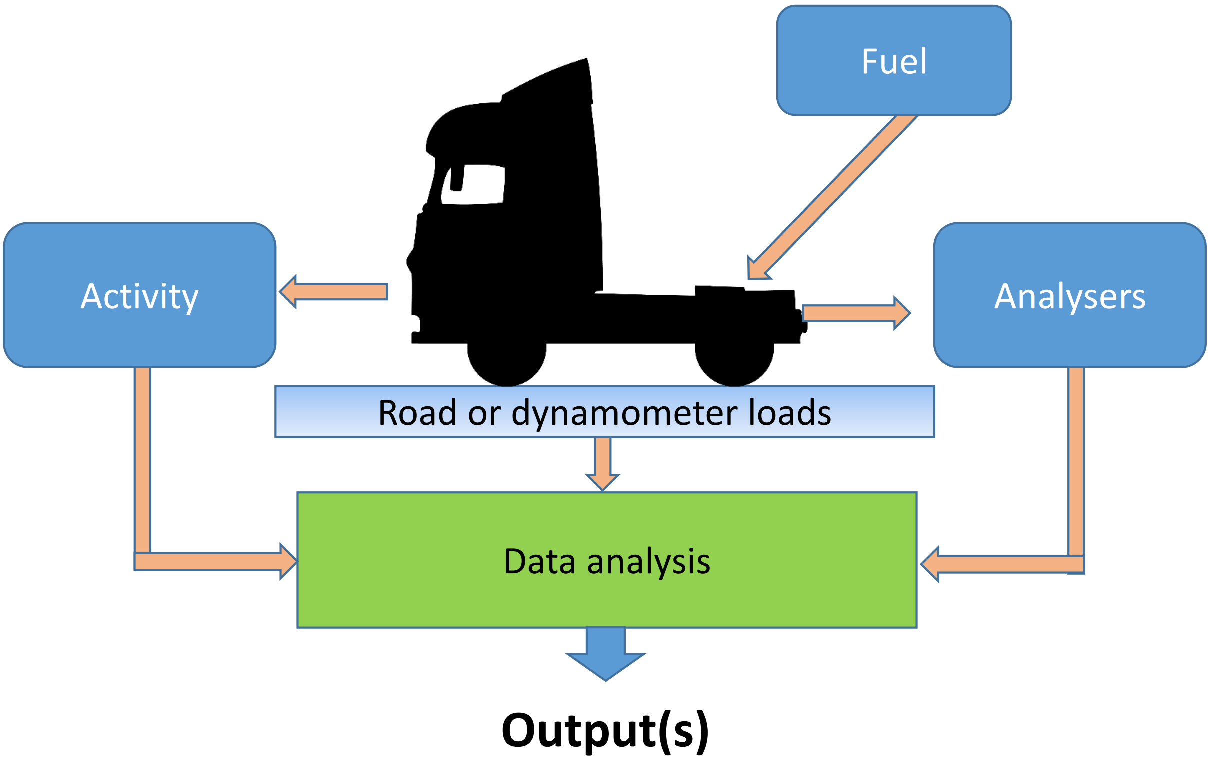
[4] Global warming potentials are expressed in terms of being relative to an equivalent mass of CO2, over a fixed period of time. The 100 year GWP for methane is given as 28 in the 5th IPCC Assessment Report (See Box 3.2 in reference http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf . However, this was revised upwards relative to the 100 year GWP for methane of 25 as given in the 4th IPCC Assessment Report and which is the current value adopted by the UNFCCC for national emission reporting. In this study we use 28, the more recent figure.

[5] *Waste and Gaseous Fuels in Transport – Final Report*. Ricardo-AEA report for DfT, July 2014.

These three deliverables comprise the outputs from three work-packages, referred to as Tasks 1, 2 and 3. This report contains all three deliverables.

A schematic representation of a test framework is provided in Figure 1-1.

Figure 1-1: Schematic of a test framework



Source: Ricardo-AEA

The test protocol involves bringing together a number of different components, measurement equipment and test conditions. These include:

1. The vehicle;
2. Fuel used by the vehicle;
3. Whether the vehicle being tested is driven on a road, is tested on a chassis dynamometer or is subjected to engine-only testing;
4. The activity it undertakes (namely, the driving cycle used under test conditions);
5. The analysers used; and
6. The subsequent data analysis performed on the results obtained from testing.

Together these elements generate an output. Each of these six aspects have been considered in turn. The overall recommended test protocol has been influenced by:

- What is to be measured/quantified;
- The conditions under which measurements are undertaken;
- The difference in measured emissions performance relative to baseline/well optimised vehicles (this influences the choice of analyser, test duration etc); and
- The level of accuracy required.

1.3 Background - methane-fuelled vehicles

1.3.1 Types of vehicles that use methane as a fuel

Methane in the form of compressed natural gas (CNG), compressed bio-methane (CBM), liquefied natural gas (LNG) and liquefied bio-methane (LBM), can be used in vehicles powered by internal combustion engines (ICE) in a number of different ways. For heavy duty vehicles (HDV) generically, which include heavy duty goods vehicles (HGV) the subject of this study, these include:

- **Dedicated methane-fuelled vehicles (including bi-fuel vehicles):** These are a development of petrol fuelled spark ignition (SI) engines. However, unlike converted petrol vehicles (see below) they are designed and optimised to use methane fuel, and manufactured accordingly. Currently their registrations comprise a small fraction of all HDVs in the UK, but as can be seen from Table 1-1, six of the seven major HDV engine manufacturers in Europe make at least one dedicated methane fuelled engine for HDVs.
- **Converted petrol vehicles:** These vehicles are converted from standard petrol fuelled, SI-engined vehicles. They are usually light duty vehicles (LDVs), are often bi-fuelled, having both petrol and methane fuel tanks, and are not considered further in this report which focusses only on heavy duty vehicles.
- **Dual-fuel vehicles:** Vehicles fitted with this type of ICE use a mixture of diesel and methane (together) in a combustion ignition (CI) engine. In this report they are abbreviated as diesel dual-fuel (DDF) engines. Fundamental thermodynamic principles mean that these engines are intrinsically more fuel efficient than their SI equivalents. The rate (both claimed and for a few vehicles actually measured) of substitution of diesel by methane varies from being low[6] (for low engine power portions of the duty cycle) to between 50% and 80% for high power operation. The benefits of dual-fuel vehicles are most apparent for long distance haulage operations, where the quantities of methane consumed make liquefied methane (LNG or LBM) the favoured fuelling option.

1.3.2 Manufacturers of methane-fuelled vehicles

A summary of the seven principal heavy duty vehicle engine manufacturers in Europe, and the Euro V methane vehicles they offer is provided in Table 1-1[7].

Table 1-1: European HDV manufacturers of methane vehicles

Manufacturer	Dedicated methane vehicle	Dual-Fuel vehicle
Iveco	Yes – Stralis	Yes, when fitted with Prins alternative fuel system
DAF (part of PACCAR)	No	Yes, when fitted with Prins alternative fuel system
Daimler (Mercedes-Benz)	Yes – Econic M 906 LAG engine	Yes, when fitted with Hardstaff OIGI dual-fuel system
Volvo (also includes Renault Trucks)	Yes – one model available	Yes as OEM Also with CAP or Hardstaff systems
Scania	Many – especially buses, but also HGVs	No
MAN	MAN's E2876 LUH 04 engine	TGS engine dual-fuel tractor
Cummins	A 330 CNG, AG 300 CNG engines	

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[6] We believe low means under 20% but this is being better quantified by on-going data collection

[7] The literature survey, and consequently table contents, cover Euro V vehicles. Some manufacturers are working on Euro VI vehicles, but these were not available for the study, and may be in the process of being certified

Links to sources of data – The information in the table above was obtained from a wide range of sources, including talking to some engine manufacturers directly, and from information publically available on the internet. A list of these sources is given in Appendix I.

1.3.3 Current heavy duty vehicle "type-approval" regulatory systems

In general, for HDVs it is the engines that are "type-approved", rather than the HDVs themselves. This is due to the high diversity of available vehicle configurations compared to the number of annual registrations. In particular, vehicle type definition that is used for light duty vehicles is not practicable for HDVs. Emission standards, and some of their principal features are outlined in Table 1-2.

Table 1-2: Emission standards and their principle features

Standard (familiar name used)	Aspect	Value
For pollutants		
Euro V	Key legislation	Directive 2006/51/EC + Directive 2008/74/EC
	Date of application for new types	1/10/2008
	Date of application for all registrations	1/10/2009
	Test cycles used	European Transient Cycle (ETC), European Static Cycle (ESC) and Dynamic Load Response (DLR)
	Are methane vehicles included?	Dedicated SI vehicles – yes Diesel – methane dual-fuel vehicles – not included
Euro VI	Key legislation	Regulation 585/2009, implemented by 582/2011 + 64/2012, 133/2014 & 627/2014
	Date of application for new models	1/1/2013
	Date of application for all registrations	1/1/2014
	Test cycles used	World Harmonised Transient Cycle (WHTC) and World Harmonised Static Cycle (WHSC)
	Additional testing	Vehicle Portable Emissions measurement System (PEMS) testing – see Regulation 64/2012
For CO_2 emissions		
-	No EU legislation currently in force but the European Commission is developing regulatory proposals for HDVs, and with this in mind is currently developing a Vehicle Energy Calculation Tool (VECTO) to support future HDV CO_2 certification processes (covered later in this report)	N/A

Directive 2008/74/EC (for Euro V) and Regulation 595/2009/EC set limit values for pollutants, for **engine test cycles**, expressed in units of milligrams of emissions (except for particle number) per kiloWatt-hour (mg/kWh), which are shown in Table 1-3. The values presented are for engines running on a single fuel, i.e. diesel or methane.

Table 1-3: Limit values for pollutants (mg/kWh)

	CO	THC	NMHC	CH_4	NOx	NH_3	PM	PN
Euro V								
ESC/ELR (diesel only)	1,500	460			2,000		20	
ETC (Diesel and gas)	4,000		550	1,100	2,000		30	
EEV ETC (Diesel and gas)	3,000		400	650	2,000		20	
Euro VI								
WHSC (CI)	1,500	130			400	10	10	8×10^{11}
WHTC (CI)	4,000	160			460	10	10	6×10^{11}
WHTC (PI)	4,000		160	500	460	10	10	6×10^{11}

Notes:

CI = Compression ignition

PI = Positive ignition (for dedicated methane engines), equivalent to spark ignition (SI)

Source: Directive 2008/74/EC and Regulation 582/2011/EC

The word "dual" does not appear anywhere in the 168 pages of Regulation 582/2011/EC (the starting regulation for Euro VI). However, in amending Regulation 133/2014 it is stated "*Whereas (3)……. type-approval and in-service conformity of engines and vehicles using dual-fuel technologies need to be provided for*." Article 3, paragraphs 45 to 56, describe the regulations for dual-fuel engines (amending Article 2 of Regulation 582/2011).

An important definition used in the Regulation is that of gas energy ratio (GER). This is defined in paragraph 50 (see Box 1). Five different types of dual-fuel engines are defined using the GER as a key parameter. These are summarised in Box 1.

The vast majority of trucks in the Low Carbon Truck Demonstrator trial are of Type 2B, i.e. they do not have to have methane fuel to run, and at idle they use only diesel fuel. Annex XVIII of Regulation 133/2014 describes the specific technical requirements for dual-fuel engines **and vehicles.** Section 5.2.2.2 of this, and its sub-sections, gives the emission limits for hydrocarbons in dual-fuel mode. This is reproduced in Box 2 below.

Box 1: Definition of gas energy ratio

Text taken verbatim from paragraph 50 of Regulation 133/2014.

"Gas Energy Ratio (GER)" means in case of a dual-fuel engine, the energy content of the gaseous fuel divided by the energy content of both fuels (diesel and gaseous), expressed as a percentage, the energy content of the fuels being defined as the lower heating value;

Dual-fuel engine type	Average GER over WHTC	Does engine idle exclusively on diesel fuel?	Does engine have a diesel mode?
Type 1A	GER_{WHTC} >= 90%	Not Allowed	No
Type 1B	GER_{WHTC} >= 90%	Not Allowed	Allowed
Type 2A	10% <= GER_{WHTC} <= 90%	Allowed	No
Type 2B	10% <= GER_{WHTC} <= 90%	Allowed	Allowed
Type 3B	GER_{WHTC} <= 10%	Allowed	Allowed

Box 2: Portion of Regulation 133/2014, Annex XVIII

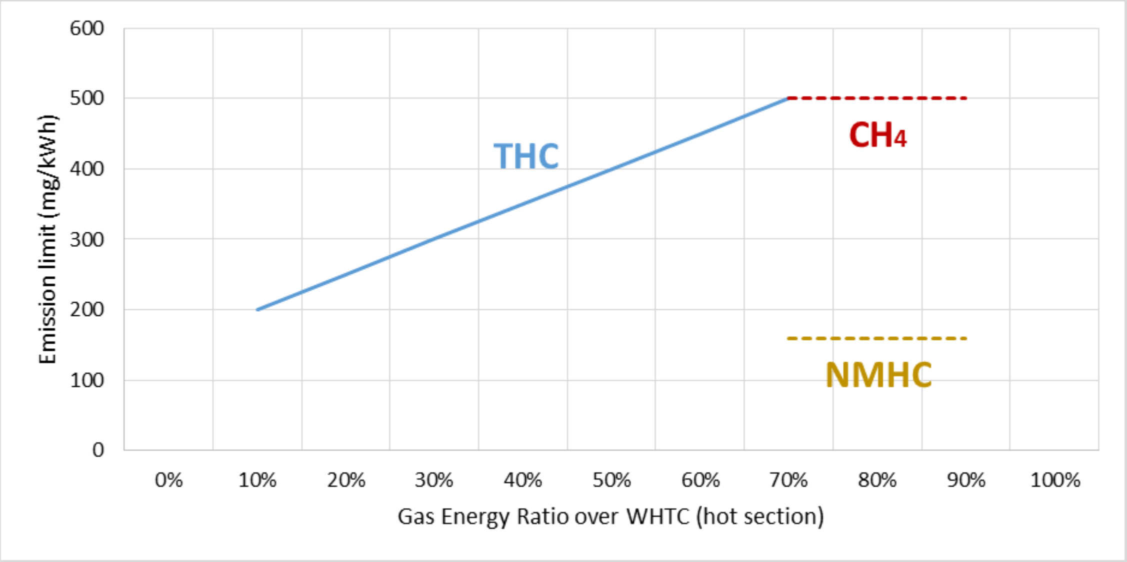
5.2.2.2 Emission limits for hydrocarbons in dual-fuel mode

5.2.2.2.1. Natural Gas/Biomethane engines

The THC, NMHC and CH4 emission limits over the WHTC test-cycle applicable to Type 2A and Type 2B dual- fuel engines operating with Natural Gas/Biomethane in dual-fuel mode are calculated from those applicable to CI and PI* engines over the WHTC test-cycle as set in Annex I to Regulation (EC) No 595/2009, in accordance with the calculation procedure specified in paragraph 5.2.3 of Annex 15 to UNECE Regulation No 49.

Practically, this means that total hydrocarbon (THC) emissions limits increase with increasing GER, from those appropriate to pure diesel vehicles to those appropriate for dedicated methane vehicles. This is shown in Figure 1-2 below.

Figure 1-2: Illustration of the HC limits in the case of a HDDF Type 2 engine operating in dual-fuel mode during the WHTC cycle (natural gas dual-fuel engines)



Source: Drawn from details described in Regulation EC 64/2012

Conformity of in-service engines or vehicles

Article 5 of Regulation (EC) No 595/2009 (*on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI)*) indicates that the Commission should adopt measures for implementing the use of portable measurement systems for verifying actual in-use emissions and verifying and limiting off-cycle emissions. This requirement has been implemented in Regulation 582/2011/EC, where the use of portable emissions measurement systems (PEMS) for the type approval process has been introduced, as part of the in-use conformity testing. Annex II of Regulation 582/2011/EC sets out the requirements for PEMS testing (European Commission, 2011). This is covered in some detail here because it is a potential guide to the regulatory framework within which any PEMS vehicle testing would be based. The structure of the information in Regulation 582/2011/EC is as follows:

- Section 3 deals with the engine or vehicle selection.
- Section 4 (page 58) deals with Test Conditions and covers:
    - Vehicle payload, specified to be 50 – 60% of maximum payload;
    - Ambient conditions, pressure > 82.5 kPa; temperature > -7 C;
    - Engine coolant temperature;
    - Fuels (use reference fuels); and
    - Trip requirements.

The Regulation regarding trip requirements is directly relevant to the choice of drive cycle for the test protocol being derived here. Different profiles are specified for different vehicle types, see Table 1-4.

Table 1-4: Drive cycle profiles by vehicle type

<table>
<tr><th></th><th>Urban
0 < V < 50 km/h</th><th>Rural
50 < V < 75 km/h</th><th>Motorway
75 < V km/h</th></tr>
<tr><td>M1 & N1 (4.5.1)</td><td>45%</td><td>25%</td><td>30%</td></tr>
<tr><td>M2 & M3 (4.5.2)</td><td>45% or 70%</td><td>25% or 30%</td><td>30% or 0%</td></tr>
<tr><td>N2 (4.5.3)</td><td>45%</td><td>25%</td><td>30%</td></tr>
<tr><td>N3 (4.5.4)</td><td>20%</td><td>25%</td><td>55%</td></tr>
<tr><td colspan="4">Further information on test conditions from Sections of Annex II (Conformity of in-service engines or vehicles, of Regulation 582/201</td></tr>
<tr><td colspan="2" rowspan="4">Distribution of characteristic trip values, from Section 4.5.5</td><td>Accelerating</td><td>26.9%</td></tr>
<tr><td>Decelerating</td><td>22.6%</td></tr>
<tr><td>Cruising</td><td>38.1%</td></tr>
<tr><td>Stopped</td><td>12.4%</td></tr>
<tr><td colspan="2">Data sampling window, see Section 4.6.2</td><td colspan="2">Prior to starting engine, but cold start emissions may be removed</td></tr>
<tr><td colspan="2">Minimum test duration, see Section 4.6.5</td><td colspan="2">5 times the WHTC work or 5 times CO_2 reference</td></tr>
<tr><td colspan="2">Electrical power supply to the PEMS equipment, see Section 4.6.6</td><td colspan="2">This shall be externally supplied</td></tr>
<tr><td colspan="2">Impact of the installation of the PEMS equipment, see Section 4.6.7</td><td colspan="2">This shall not influence vehicle emissions or performance</td></tr>
<tr><td colspan="2">Basic operation, see Section 4.6.8</td><td colspan="2">The vehicle should be operated under normal daytime traffic conditions</td></tr>
</table>

Source: Derived from European Commission, Regulation 582/2011/EC

Guidance is given on acceptable levels of emissions. These are:

- Emissions levels for CO, THC, NMHC, CH_4, NOx, are to be ≤ conformity factor multiplied by the type approval WHTC standard (as given in Table 1-3);
- The maximum conformity factor is 1.50; and
- For PM mass and PN – not quoted in the Regulation as assumed not to be measured.

Important consequences of the above are:

- PEMS equipment is used to take measurements from complete vehicles, rather than just engines; and
- The limit is specified in the Regulation in terms of mass of emissions/kWh (not per km).

In the amendment to the Euro VI Regulation, Regulation 64/2012 specifies in its Appendix 1 – PEMS demonstration test at type approval. This confirms the payload should be 50 – 60% of maximum payload, and for ambient conditions, fuel, lubricants, reagent, trip and operational requirements are as specified in Regulation 582/2011.

2 Literature review

2.1 Methane slip

Methane slip is the unburned methane emitted from the tailpipe. Methane can also be emitted from other parts of the engine and from fuel tanks (venting). Methane emissions are of particular concern, as methane is a GHG with global warming potential (GWP) 28 times that of CO_2 on a weight for weight basis[8]. Therefore, in sufficient quantities, its emissions may counterbalance any CO_2 savings achieved through the switch from diesel.

Methane is part of the mix of unburned hydrocarbons emitted from the tailpipe of both diesel and petrol engines, although not in significant quantities. It is far more significant for internal combustion engines using methane as a fuel.

2.1.1 Methane emissions

There are a number of studies which attempt to quantify CH_4 emissions from HDVs which have been identified in the preparation of this report. However, they often present results for very different types of vehicle including methane-fuelled buses, and the range of estimates is extremely wide. The limited amount of data on tailpipe emissions of methane from gas-fuelled vehicles, and their wide range, is largely due to the lack of regulation in the transport sector for these specific type of engines.

A study conducted by AVL (2014), *Enhanced Emission Performance and Fuel Efficiency for HD Methane Engines,* investigated the extent of current methane deployment and future potential of natural gas (NG) deployment in HDVs. The main conclusions related to diesel dual-fuel engines and converted petrol engines are summarised in Table 2-1 below.

Table 2-1: Methane deployment in diesel dual-fuel and converted petrol engines

Diesel dual-fuel (Methane diesel) concepts:	Dedicated spark ignited engines (SI)
• Very difficult to meet mandatory emission standards (Euro V, Euro VI) with present available technology • Suitable technology only possible for OEM applications • Gas energy ratio (GER) very much dependent upon load conditions and is often lower than target expectations Total emissions of GHG might be higher in dual-fuel mode than for vehicles operating on diesel fuel only because of methane slip, despite the lower carbon intensity of methane relative to diesel	• Usually no problem to meet Euro V/EEV emission requirements provided an appropriate catalyst is present • Engine efficiency lower for SI applications compared to diesel especially for lean-mix applications (18% vs. 33%) (The lean-mix concept is where the fuel mixture alternates between stoichiometric and lean-burn combustion)

Source: AVL, 2014

The report includes both Portable Emissions Measuring System (PEMS) and chassis dynamometer tests of emissions for different combinations of methane-fuelled engines. However, tailpipe methane emissions could not be measured and only chassis dynamometer results are reported, as shown in Table 2-2.

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[8] The 100 year GWP for methane is given as 28 in the 5th IPCC Assessment Report, an upward revision to the figure of 25 given in the 4th IPCC Assessment Report and which is the current value adopted by the UNFCCC for national emission reporting. In this study we use 28, the more recent figure.

Table 2-2: Methane emissions test results for three different types of gas engines

	Chassis Dynamometer drive cycle	Methane emissions		Energy efficiency
		g/km	g/kWh	
Dedicated SI lean/mix gas engine (Note 1)	Average WHVC cold start	0.72	0.81	18%
	Average WHVC warm start	0.17	0.20	19%
	FIGE	0.39	0.46	19%
Dedicated SI lean-burn gas engine (Note 2)	Average WHVC cold start	1.65	1.83	26%
	Average WHVC warm start	0.37	0.41	27%
	FIGE	0.48	0.56	31%
Diesel Dual-Fuel Vehicle – DDF1 CAP (OEM/Retrofit)	WHVC cold DDF	6.12	6.53	38%
	WHVC warm DDF Average	8.60	9.17	51%
	FIGE DDF Average	7.02	8.66	45%

Note 1 – A dedicated CNG bus where the fuel mixture alternated between stoichiometric and lean-burn combustion

Note 2 – A CNG vehicle where the fuel mixture was consistently lean-burn combustion

WHVC – World Harmonised Vehicle Cycle

FIGE – FIGE Institute (Germany)

DDF – Diesel Dual-Fuel

Source: AVL, 2014

The final report of a recent study for the Department for Transport (DfT), entitled: *Waste and Gaseous Fuels in Transport* (Ricardo-AEA, 2014) identified a high level of uncertainty surrounding the issue of tailpipe methane emissions in gas fuelled HDVs, as well as uncertainty regarding methane substitution rates which will influence those emissions. Discussions with stakeholders identified methane slip in the range of 1-5% for the first generation of dual-fuel vehicles, a variability confirmed by the analysis of other written sources. The report concludes that if methane slip were to be about 2% or above, then there would be no GHG emissions saving compared to diesel only operation, a figure that would depend heavily on the achieved substitution rate. The report includes an overview of tailpipe methane emission factors for a range of dedicated methane vehicles, drawn from IPCC and EPA sources (see Table 2-3).

A series of tests run by AVL (2014) on tailpipe emissions arrived at very similar conclusions to the Ricardo-AEA (2014) study. AVL concluded that, based on measurements of tested technologies, the tailpipe GHG emission benefit of replacing diesel fuel with methane gas is marginal.

It was noted that, while CO_2 emissions will be reduced when replacing diesel with methane, CO_2 equivalent emissions (CO_2 + CH_4 g/km) of dual-fuel HGVs (operating in dual-fuel) may be higher than the diesel comparator vehicle due to methane slip. This was the case for one of the three dual-fuel vehicles tested. For another vehicle, although there was significant methane slip, overall there was a small reduction in GHG emissions (see Figure 2-1).

Table 2-3: Tailpipe methane emission factors for dedicated methane vehicles

Vehicle type	Fuel	Vehicle selected	CH_4 (mg/km)	Reference
Large van (light duty vehicle)	Diesel BtL diesel	Mercedes-Benz Sprinter 316	1	Euro 4 diesel van, IPCC guidebook, See note 1
Large van (light duty vehicle)	CNG, CBM	Mercedes-Benz Sprinter 316	1	Identical figure to above for this drop-in fuel
Medium size rigid truck (HGV)	Diesel	Iveco Eurocargo (12-16 t) 120E20L 4815 150 kW	30	<16 t diesel truck, Table 3.2.5 IPCC guidebook, See note 1
Medium size rigid truck (HGV)	CNG, CBM	Iveco Eurocargo as in Table 2	1,220	Table A-7 of EPA guidebook, see note 2
Refuse collection vehicle (HGV)	Diesel	Mercedes-Benz Econic, 1830 LL Rigid 220 kW	90	>16 t diesel truck, Table 3.2.5 IPCC guidebook, See note 1
Refuse collection vehicle (HGV)	CNG, CBM, LNG, LBM	Mercedes-Benz Econic, as in Table 2	1,220	Table A-7 of EPA guidebook, see note 2
44 tonne Articulated truck (HGV)	Diesel	Volvo D13C460 diesel 338 kW (13 litre) in FM13 chassis	90	>16 t diesel truck, Table 3.2.5 IPCC guidebook, See note 1
44 tonne Articulated truck (HGV)	LNG, LBM	Volvo D13C Gas methane /diesel as in Table 2	650	Estimate, 50% diesel vehicle, 50% CNG vehicle
City bus (HDV)	Diesel	MAN Lion City bus with D2066 LUH EEV 10.5 litre Euro VI diesel engine (265 kW)	30	<16 t diesel truck, Table 3.2.5 IPCC guidebook, See note 1
City bus (HDV)	CNG, CBM	MAN Ecocity bus as in Table 2	60	From MAN data

Note 1 - For conventional vehicles data source is IPCC Inventory handbook, Table 3.2.5 for European vehicles (EPA data will be for vehicles meeting different (US) emission standards)[9]

Note 2 - For alternatively fuelled vehicles data source is EPA Inventory handbook, as discussed in the text[10].

CBM – Compressed Bio-methane	*LBM – Liquid Bio-methane*
LNG – Liquid Natural Gas	*CNG – Compressed Natural Gas*

Source: Ricardo-AEA, 2014

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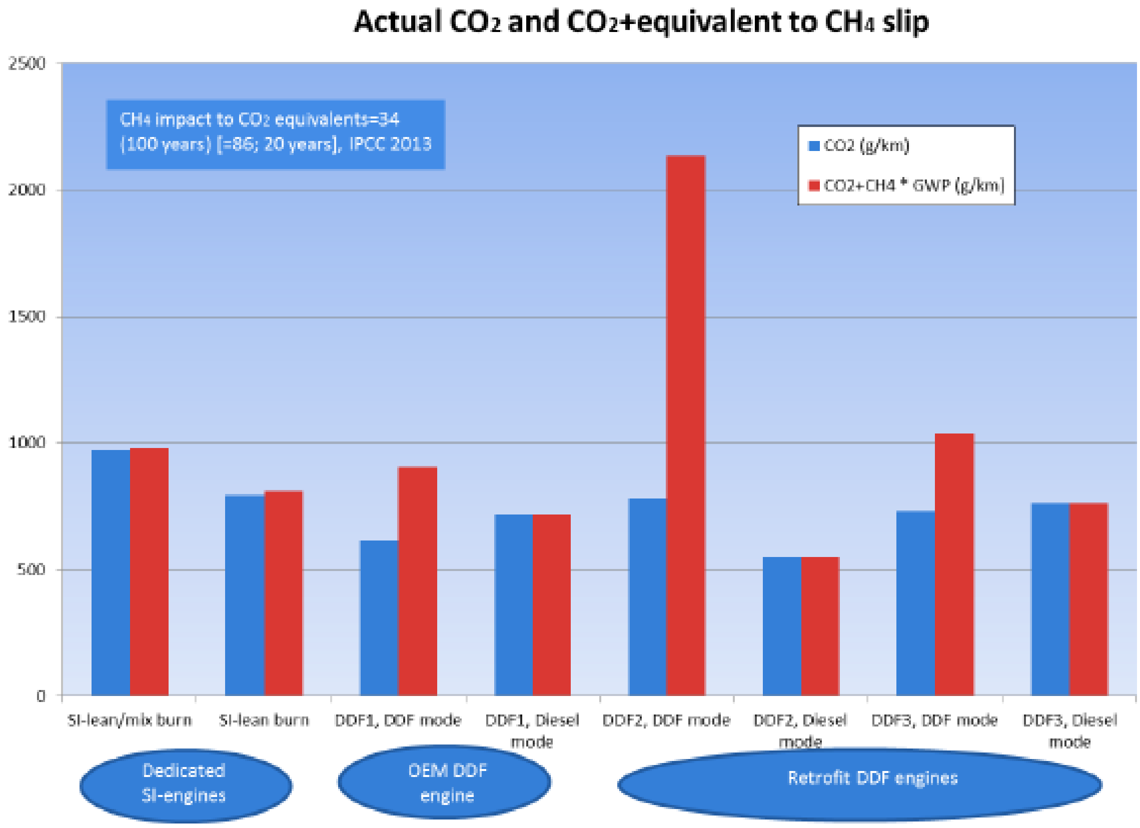
[9] from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf

[10] Available from: http://www.epa.gov/climateleadership/documents/resources/mobilesource_guidance.pdf

Figure 2-1: Equivalent CO_2 emissions from different concepts



Source: AVL, 2014

Note – the table above from AVL uses a GWP of 34, rather than the figure of 28 used in this study (and recommended in the 5th IPCC Assessment Report). Replacing the GWP used with the factor of 28 would have the effect of **reducing the height** of the red columns (which include methane emissions). The size of the reduction would depend on the CO_2 to methane contribution, being 17.6% of the difference between the CO_2 contribution, the blue column, and the combined GHG emissions, the red column.

The European Environment Agency's (EEA) technical guidance used in the preparation of national emission inventories includes methane emissions estimates as shown in Table 2-4 (EEA, 2013). However, it should be appreciated that these are values for a range of vehicle sizes and technologies. The emission factor for total hydrocarbons (i.e. methane + NMVOC) for Euro V trucks (discussed in Section 3.2.1 on Comparator Vehicles) is less than 50 mg/km. Hence, the methane emission figures implied from the data in Figure 2-1 appear high relative to generally accepted figures given in Table 2-4.

Table 2-4: Methane (CH_4) emission factors (mg/km)

Fuel	Vehicle technology/class	Methane emission factors (mg/km)		
		Urban (Hot)	Rural	Highway
Petrol	All technologies	140	110	70
Diesel	GVW <16t	85	23	20
	GVW >16t	175	80	70
	Urban buses and coaches	175	80	70
CNG	Euro I	6800		
	Euro II	4500		
	Euro III	1280		
	EEV	980		

Note: Weight classes of heavy-duty vehicles correspond to Gross Vehicle Weight, i.e. the maximum allowable total weight of the vehicle when loaded, including fuel, passengers, cargo, and trailer tongue weight.

EEV - Environmentally Enhanced Vehicles, as defined in the EC Directives, e.g. Directive 2008/74/EC for Euro V

Source: EEA, 2013

It is notable that even in the 2013 version of the EMEP/EEA air pollutant emission inventory guidebook there are no data for CNG fuelled Euro IV, V or VI vehicles. Close reading of the text also indicates that the values tabulated are somewhat out of date.

The EEA also provides estimates of emissions reduction factors over Euro I figures. However, the table does not include any technology in relation to methane powered vehicles. This variability is confirmed by other sources. For example, Argonne National Laboratory[11] quotes US Advanced Motor Fuel[12] and provides the values set out in Table 2-5 below.

Table 2-5: Methane emission factors for selected types of methane-powered vehicles

Vehicle Type	Emission Factor
CNG+TWC transit buses/trucks:	2750 mg/km
Diesel Euro IV/EEV + emission control bus:	<15 mg/km
CNG + TWC bus:	151 mg/km

These figures illustrate how variable methane emissions can be. In part this arises from trying to compare emissions from different types of vehicles (e.g. urban buses vs long-haul trucks), manufactured at different points in time (and hence fitted with emissions control equipment of varying levels of sophistication), used over different driving cycles.

Projects in the Low Carbon Truck Trial will attempt to estimate the extent of methane slip from vehicles and during refuelling[13]. The US Environmental Defence Fund (EDF) is also sponsoring a study to quantify methane leakage associated with the use of natural gas in the transport sector, in cooperation with several research institutes and freight operators. The study is looking at emissions from the whole value chain, and will include the quantification of tailpipe emissions from HDVs[14]. Emissions testing will

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[11] http://www.afdc.energy.gov/pdfs/anl_esd_10-4.pdf

[12] http://www.iea-amf.org/content/fuel_information/methane

[13] http://www.gasvehiclehub.org/low-carbon-truck-trials/11-lcct/41-entris

[14] http://blogs.edf.org/energyexchange/2013/03/04/study-intends-to-determine-methane-leakage-associated-with-a-growing-natural-gas-transportation-sector/ and http://www.theicct.org/news/icct-joins-edf-wvu-study-methane-emissions-hdvs

help to evaluate the scale of the problem and the effectiveness of potential solutions. Whilst articles highlighting this research indicate that it sought to publish a report in 2014, the EDF's web-site does not contain either a published report, or a revised date for publication.

2.1.2 Causes of methane slip

Methane slip is generally caused by methane not being completely burnt in an engine's combustion chamber. In spark ignition (SI) engines there are several mechanisms that lead to some of the fuel mixture evading the combustion process, including the following:

- The principal mechanism is due to *crevice losses*: the fuel mixture is forced into narrow crevices (such as the piston ring pack and the head gasket crevice) which quenches the flame propagation, leaving that part of the mixture unburned. This then returns to the combustion chamber from the crevice when the cylinder pressure drops, where it is mixed with exhaust gases and expelled.
- Other parts of the air-fuel mixture escape the combustion process by being absorbed into the oil film of the cylinder walls (*adsorption*) and then released when pressure drops (*desorption*);
- Also, combustion quenching affects the gaseous mixture next to the cylinder walls. This portion of the mixture generally has a lower temperature than the bulk of the combustion chamber. This factor is particularly relevant for methane, as its auto-ignition temperature is 580°C, compared to 280°C for petrol (The Engineering Toolbox, undated).

These processes are further aggravated in lean burn engines, as they operate at lower temperatures.

In general, the factors listed above are engine topology dependent (Königsson, 2012). However, they can be more severe because of poor transient control and/or ignition system quality. However, if the fuel and ignition system is properly designed and calibrated, these losses can be markedly reduced[15]. Also, as will be seen in Section 2.2, exhaust after-treatment catalysts have an important role to play.

Diesel-fuelled compression ignition (CI) engines are not affected by crevice losses, adsorption and quenching because the fuel is directly injected into the combustion chamber at a time in the engine cycle and a position in the combustion chamber deliberately chosen to avoid these. Königsson identified the following sources of losses and inefficiencies for diesel engines:

1. Overmixing of fuel and air during ignition delay;
2. Overriching of the mixture beyond stoichiometric; and
3. Fuel escaping from nozzle sac during expansion.

The amount of hydrocarbons emitted from diesel engines is, however, much lower than from petrol fuelled engines, and optimised engine calibrations can greatly reduce the losses at point 1 to 3.

In the case of Diesel Dual-Fuel (DDF) engines, emissions of hydrocarbons become more important, because DDF engines partly resemble CI engines and partly resemble SI engines, particularly with respect to a substantial part of fuel being admitted with the charge air. Königsson identifies the following causes that may lead to hydrocarbon emissions:

1. **Combustion chamber crevices:** Volume between the crown first ring, and ring pack crevices are likely to be the most influential crevices in a dual-fuel engine. The amount of mixture that ends up in the crevices varies with the combustion process; it is higher in stoichiometric and lower in lean burn due to pressure differences. However, the higher temperatures reached in the former case allow the mixture to burn after they emerge from the crevices and before the Exhaust Valve Opening (the close part of the cycle). Most of today's DDF engines use a lean burn cycle, which burns at lower temperatures and does not allow the mixture to burn in the closed stage.
2. **Flame quenching, both near surfaces and in the bulk mixture:** This occurs when the air-fuel mixture does not reach the correct temperature for combustion to be sustained. It is more common near cylinder walls and, in some cases, can occur in the bulk mixture.
3. **Absorption and desorption in deposits:** Generally leads to minimal hydrocarbon emissions

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[15] http://www.biogasmax.eu/media/d5_10_biogasmax_brg_v1final_march2010__008585200_0948_26012011.pdf Page 21

4. **Fuel escaping from nozzle sac during expansion**: Minimal amount of methane slip (losses would be mostly unburned diesel).
5. **Fuel escaping directly from inlet to exhaust port[16]:** In diesel engines, where the liquid fuel is injected at carefully controlled times, it may be that the inlet port opens before the exhaust port closes. This would occur well ahead of any fuel injection, which is timed for close to the top of the compression stroke, when both valves are shut. However, in a dual-fuel engine, the methane is often added with the inlet air. Under these circumstances some methane can move across the top of the cylinder into the exhaust stream, never experiencing a power stroke.

2.1.3 Research quantifying methane slip

A much more detailed study was undertaken by Stettler et al. and reported at the 18th ETH Conference on Combustion Generated Nanoparticles[17]. This team collected data at a large number of steady states, and constructed colour maps (rather than contour maps) of engine speed as the horizontal axis and engine load as the vertical axis. Maps were often presented as pairs, with diesel comparators and the dual fuel map side by side.

Whilst the focus of the presentation was on nanoparticle emissions from heavy-duty and dual fuel diesel and natural gas engines, it contained useful information pertinent to this study. However, there is the caveat that this in depth study is for a single engine. The base vehicle was a DAF CF 75 fitted with a PACCAR PR 228 kW Euro V engine that had been converted by Prins in March 2014. The engine had SCR after-treatment and had no methane catalyst at the time of the reported study. It was reported that there are plans to add one towards the end of 2014, but no further data has been published by March 2015.

The energy substitution ratios in this study were low at low engine speeds and at low torques. Maximum substitution rates were 50% or above at engine speeds around 1600 rpm and a torque around 250 Nm (42 kW).

For motorway driving, this vehicle's engine would be operating at 1500 rpm and between 600 and 900 Nm. At 1500 rpm and 600 Nm (95 kW) the substitution ratio is close to 50%. At this point on the engine's map CO_2 emissions are around 12% lower than the same vehicle operating in diesel only mode.

A map of methane slip is also given, although the units for this scale are not known, those provided being incorrect. However, the legend for the figure suggests there may be 10% methane slip at 1500 rpm and 600 Nm. This is confirmed in a later slide where the total GHG emissions are mapped. The CO_2e emissions at this speed/load point are 30% higher than the diesel comparator

The other important feature from this figure is that methane slip is largest at low torque operation for all speeds, but with extensive slip occurring up to 400 Nm at 800 rpm and 800 Nm at 2200 rpm.

The final part of the presentation focuses on how this is relatively early research, and speculates on the reductions in methane slip that should occur through the fitting of a catalyst.

In a more recent communication more recent data were shared. These covered the effect of averaging different periods of modal, or PEMS, data, and whether CO_2 is a reasonable proxy for engine power. The following two figures show CO_2 emissions, and brake-specific fuel consumption plotted as a colour – engine speed – torque map for a dual fuel diesel/methane truck.

Figure 2-2: CO_2 Emissions per kWh as a function of engine speed and torque

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[16] This mechanism was identified in consultation with other stakeholders, not via the Königsson reference

[17] M Stettler, W Midgley, D Cebon & A Boies, Paper given to 18th ETH Conference on Combustion Generated Nanoparticles, see http://www.lav.ethz.ch/nanoparticle_conf/Former/2a-4_Stettler.pdf. ETH is the *Eidgenössische Technische Hochschule, the Swiss Federal Institute of Technology in Zurich.*

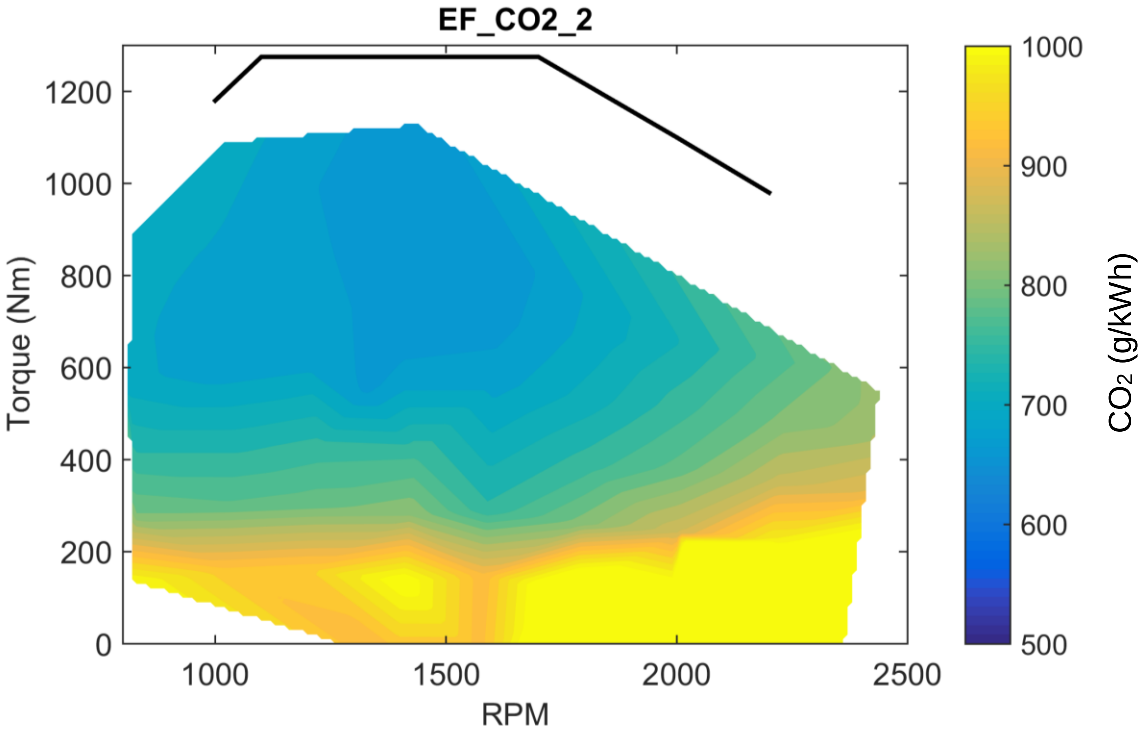
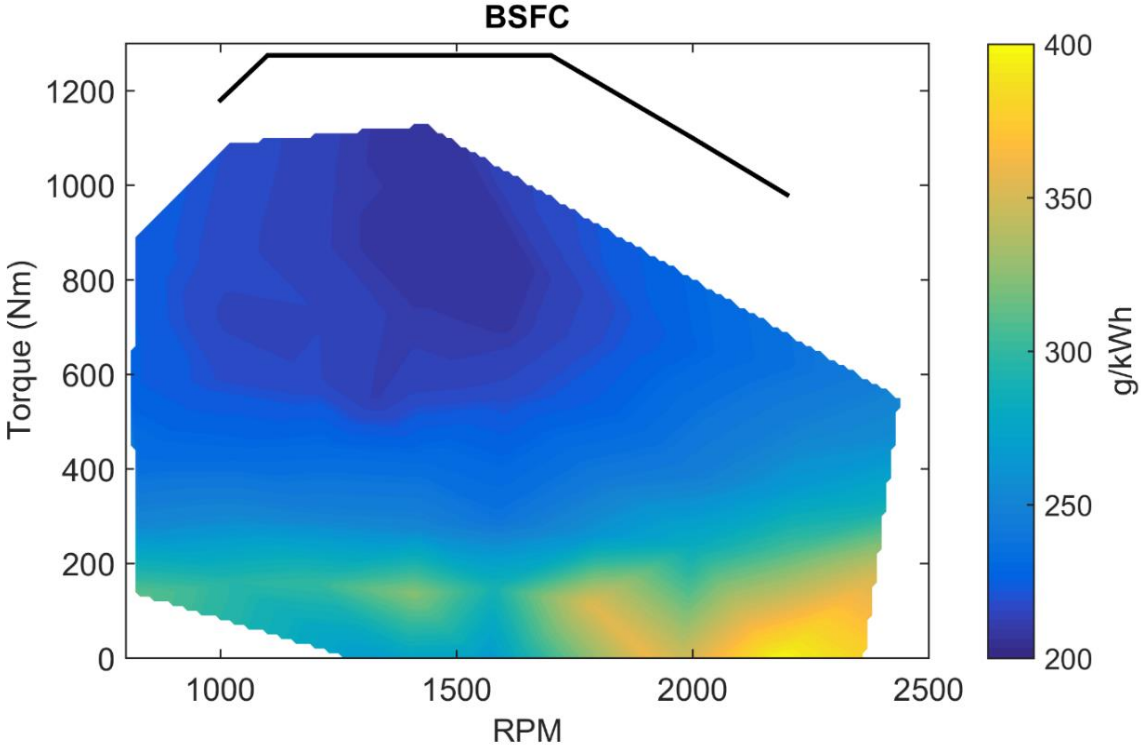


Figure 2-3: Brake specific fuel consumption per kWh as a function of engine speed and torque



Original source of both figures: M Stettler, University of Cambridge, Private Communication, March 2015

These figures provide a quantification regarding the extent to which CO_2 can be taken as a direct proxy for the work done by the engine. Overall, it can be regarded as having a moderate correlation. In the mid-speed and torque range, e.g. 1000 – 2000 rpm and 500 – 600 Nm ranges the CO_2 emissions are around 800 g/kWh. At higher torques this reduces by up to 20%, and at lower torques the CO_2 emissions per kWh increases by up to 20% with the exception of when operating at very low torques where emissions are even higher. However, for a moving vehicle it will not spend very much time in this region of operation.

Figure 2-3 gives a similar message, but from the perspective of fuel consumption.

These data indicate the limits of the assumption that CO_2 emissions may be related to kWh produced by the engine for a dual fuel vehicle.

2.1.4 Information from the Low Carbon Truck Demonstration Trial Evaluation

In addition to the previously cited and discussed literature, recent information is becoming available from the “Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation” project, and some linked studies. The trial is being led by a joint study team from Cenex and Atkins.

The first annual report to the DfT on this project, written by Atkins in June 2014, contains some broad information relevant to this project on methane slip[18]. It starts the section on trial data analysis with the following caveat: “The performance analysis presented should be considered as provisional as it is based on a relatively small amount of data, provided by a low number of consortia over a limited period”.

On substitution ratio it reports: “The average substitution ratio (the percentage of diesel fuel replaced by gas in dual fuel mode) is 46% from the dual fuel gas. The substitution ratios of the trucks are on an upward trend as early problems with infrastructure, fuel availability (leading to some vehicles having to cover part of their journeys in diesel only mode) and vehicle reliability are receding”.

On CO_2 substitution it reports: “The first monitoring data shows that fleets are experiencing CO_2 emission savings from the gas dual fuel vehicles of up to 9% on a tank to wheel (TTW) basis and up to 6% on a well to wheel (WTW) basis. The low average emission savings are mainly due to some fleets experiencing relatively high efficiency losses at present as manufacturers are working to improve their systems, as well as additional factors such as gas availability issues (leading to some vehicles having to cover part of their journeys in diesel only mode). No data are offered regarding other emissions”.

Notwithstanding these issues, the information above does offer some useful insight into the level of methane slip that would cancel out the CO_2 emissions reductions for the dual fuelled vehicle. If typically CO_2 emissions are around 800 g/km, and CO_2 emissions savings are 9%, then this corresponds to savings of 72 g CO_2/km. From the perspective of global warming potential, methane slip emissions of 2.6 g/km would be equivalent to an increase in CO_2 emissions of 72.8 g CO_2/km (100 year GWP for methane taken as 28) – i.e. this is the amount of methane slip emissions that would negate the reduction in CO_2 emissions from fuel combustion due to shifting from diesel to methane.

Cenex have confirmed that the above analysis is broadly correct from their collection of data for year 2 of the trial. Some data had been collected from an early implementation of the dual fuel technology and high levels of methane slip had been observed in some circumstances. However, this information does not indicate at which points in the engine speed-load profile, or at which speeds for on the road driving, the methane emissions are higher, and at which points they are lower.

The important factors from the research reviewed in this section relevant to this study into methane slip are:

- The estimations regarding methane slip emissions that cancel the CO_2 savings are confirmed;
- Methane slip can be significant at all engine speeds; and
- Methane slip is indicated to be higher for lower torque values, and is high at the typical engine speeds required for motorway driving.

This provides guidance regarding the range of driving cycles appropriate for measuring whether methane slip is occurring.

It has also become clear that, due to limitations in the data quantifying the changes in CO_2 emissions in the dual fuel mode, it should not be used as a basis for calculating the changes in GHG emissions. Rather, independent, accurate measurements of changes in CO_2 emissions should be part of the emissions testing protocol specified by this study. This, when combined with the range of speeds over

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[18] The first annual report to the DfT on the “Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation” project, available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/321248/low-carbon-truck-trial.pdf

which methane emissions were seen to occur, supports the view that the test protocol's driving cycle should cover urban, rural and motorway driving conditions.

Fugitive emissions

Storage of methane on board vehicles is also a challenge. Methane is gaseous at ambient temperatures, and in order to store significant quantities of methane it either has to be compressed or liquefied (when it is stored in cryogenic tanks). In liquefied form it has an energy density comparable to diesel or gasoline[19]. However, both these storage options can leak, or generate gaseous boil off. These non-tailpipe emissions are known as fugitive emissions. They are analogous to the petrol vapour lost from petrol vehicles, and are potentially important. However, they are outside the scope of this study.

2.2 Exhaust after-treatment technologies

The principal exhaust after-treatment technology used to remove hydrocarbons, which include methane, from the exhaust is an oxidation catalyst. The fundamental chemical reaction that occurs for methane can be written:

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$$

i.e. methane is oxidised to carbon dioxide and water. The C:H ratio for other hydrocarbons varies but for liquid fuels this is markedly less than 4.0. For saturated aliphatic alkanes, their general chemical formula (C_nH_{2n+2}). For octane, the typical carbon chain length for petrol, n = 8 and the ratio is 2.25, while for dodecane, the carbon chain length for petrol, n = 12, and the ratio is 2.17. For alkenes with a single double bond, whose general formula C_nH_{2n}, the ratio is 2.00, whilst for benzene (C_6H_6) it is 1. If fuels can, on average, be depicted generically as CnH2n, the combustion analogous equation is:

$$C_nH_{2n} + 1\tfrac{1}{2}\ n\ O_2 \rightarrow nCO_2 + n\ H_2O$$

i.e. all hydrocarbons are oxidised to carbon dioxide and water.

Temperature is a crucial factor in the efficiency of the catalytic process, in particular the temperature at which hydrocarbons are oxidised to carbon dioxide and water. Methane is a relatively stable hydrocarbon and requires the highest oxidation temperature of all hydrocarbon gases. The chart below shows the conversion efficiency of an oxidation catalyst for different hydrocarbons versus gas temperature[20]. Therefore, a catalyst designed to remove the hydrocarbons from the exhaust of either a petrol or diesel fuelled vehicle, may be poor at oxidising methane. With reference to the figure below, when operating at 425°C, where 90% of ethane and propane would be oxidised, only about 20% of methane would be oxidised. Furthermore, conversion efficiency of methane barely exceeds 90% even at 500°C.

A direct consequence of this temperature sensitivity is that the protocol to test methane slip should consider the temperature of operation, e.g. by measuring exhaust temperatures. This will vary with engine load, and consequently the payload of the vehicle.

Another factor, evident from the chemical equations for the oxidation of methane and other hydrocarbons, is that methane requires more oxygen, and consequently more air, for its oxidation.

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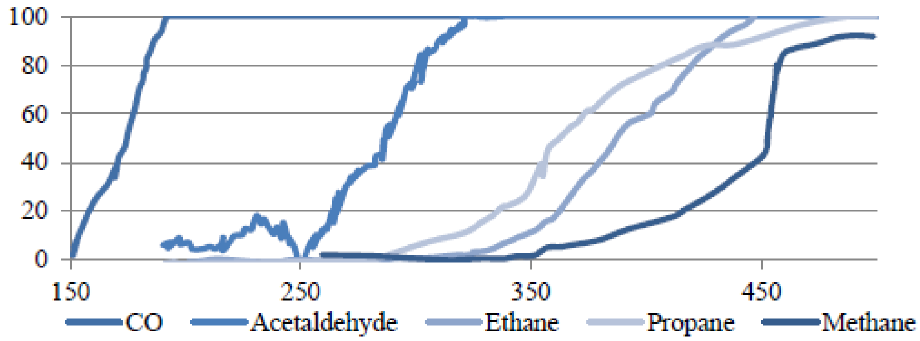
[19] http://www.diva-portal.org/smash/get/diva2:533308/FULLTEXT01.pdf

[20] http://www.diva-portal.org/smash/get/diva2:533308/FULLTEXT01.pdf

Figure 2-4: Conversion efficiency of an oxidation catalyst versus gas temperature for different hydrocarbons



Source: Figure 4 from thesis on: "Advancing the limits of dual fuel combustion", F Könligsson, 2012

The important consequence of the above is that a catalyst designed to remove hydrocarbons for a petrol fuelled vehicle (part of what is often called a three-way catalyst) or for a diesel fuelled vehicle (what is often called a diesel oxidation catalyst) **is most probably not designed to effectively oxidise methane.** Therefore, for methane vehicles specialised methane catalysts have had to be developed.

Hydrocarbons other than methane (NMHCs) are generally controlled with catalysts containing palladium and platinum supported on monoliths. Catalytic oxidation approaches to control methane emissions from methane fuelled vehicles are more complicated than for NMHCs, due to methane's higher stability. Furthermore, sulphur is a catalyst poison, inhibiting the oxidation process[21]. Sulphur is present in a range of methane fuels, naturally, or is deliberately added in the case of natural gas.

- Fossil petroleum contains sulphur, which is reduced at the refinery. Successive fuel standards have lowered the maximum level permissible such that it is now 10 ppm (by mass) for both diesel and petrol. The driver for this reduction has been the need to protect catalysts.
- Similarly, fossil methane often contains small amounts of sulphur.
- Natural gas has a sulphur containing compound added for safety reasons. This gives it an odour, whereas pure methane is odourless. The compound usually used is ethyl mercaptan (C_2H_5SH) which is added at a rate of around 4 ppm (by mass).
- Biogas from anaerobic digesters often contains quantities of sulphur compounds, the major source of their smell. This is reduced during the up-grading process, when nitrogen, carbon dioxide and other non-fuel components are also greatly reduced.

Because of its inhibiting of catalytic activity, sulphur control is important (the principal control of this is through low maximum sulphur concentrations being specified in fuel standards, and regulations).

A further aspect of methane catalysts is that not only should they effectively oxidise methane but they may also lead to the conversion of nitric oxide, NO, to nitrous oxide, N_2O, a GHG with a GWP of 265. This is very significantly higher than the GWP values of methane (GWP = 28) and CO_2 (GWP = 1)[22]. Any emissions of N_2O from methane-fuelled vehicles would further offset the benefits of reducing methane emissions[23] and its avoidance is important.

The type of exhaust after-treatment required for methane-fuelled vehicles depends on the type of combustion used - lean burn or stoichiometric. From an engine construction point of view, lean burn engines are simpler and cheaper to build and therefore are more common. However, NOx emissions associated with lean burn combustion are higher, and there is consensus that it will be very difficult to reduce them without further development of catalytic converters. These may include Selective Catalytic Reduction (SCR) systems for these spark ignition engines, building on the experience and expertise

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[21] http://www.sciencedirect.com/science/article/pii/S0926337397000246#

[22] Global warming potentials are expressed in terms of being relative to an equivalent mass of CO2, over a fixed period of time. The 100 year GWP for methane and N_2O given here are those from the 5th IPCC Assessment Report (See Box 3.2 in reference http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf .

[23] Waste and Gaseous Fuels in Transport – Final Report

gained from the use of SCR with CI engines. Stoichiometric natural gas engines deliver fewer emissions but are less efficient, operate at higher temperature and are generally more expensive to convert. The application of Exhaust Gas Recirculation (EGR) systems may improve fuel efficiency, reduce NOx and allow engines to operate at lower temperatures[24].

Some of the best catalysis for methane oxidation are palladium based, dispersed on alumina or zirconia support matrices. However, they tend to deactivate through loss of active surface by sintering and by transformation into metallic Pd at temperatures above 600 °C.[25]

The available literature indicates that methane catalysts studied add around £5,000 to the price of the vehicle[26] and have very poor durability[27,28]. However, it may be that there have been recent advances and this information is out of date.

2.2.1 Types of catalysts

There are four of types of catalysts, which are commonly used in automotive exhaust after-treatment, and these are described in more detail below.

- **Three-way catalyst:** Used in stoichiometric SI engines, it reduces HC, CO and NOx emissions. Its maximum efficiency is reached when the engines operates at $\lambda=1$, and generally requires the use of Pt (Platinum), Pd (Palladium) and Rh (Rhodium) in relatively low quantities, which make it a rather cost-efficient solution. However, they are relatively poor at capturing methane emissions.
- **Oxidation catalyst**: Increasing the air/fuel ratio ($\lambda>1$) allows for increasing engine efficiency, reducing the amount of unburnt methane into the tailpipe. Lean burn spark ignition engines operate at lower temperatures and heavy duty SI engines can suffer from misfiring, which has negative impacts on the catalyst. For this type of engine, an oxidation catalyst promotes the oxidation of HC and CO. However, lean burn engines also increase NOx emissions and require the installation of exhaust after-treatment technology to reduce these emissions. Oxidation catalysts are also detrimentally affected by the sulphur content of natural gas. This is a further challenge to be addressed.
- **Diesel Oxidation Catalyst:** Converts CO and hydrocarbons into carbon dioxide and water, as discussed earlier, using oxygen. NOx emissions are addressed with the use of EGR, SCR or NOx traps.
- **Selective Catalytic Reduction (SCR):** SCR catalysts use urea as a reagent to chemically reduce NOx to nitrogen and water. They are widely used for Euro VI heavy duty trucks in order to meet the low NOx emission standards. They have no oxidising action, and will not affect methane concentrations directly. The design of a SCR system, however, becomes slightly more complicated for dual-fuel engines, because of the need of an oxidation catalyst to reduce methane slip.

In addition, a novel approach is being researched. The fundamental chemistry was only proven in 2012, and any use in vehicles is still many years away. This new type of catalyst is known as a core-shell heterogeneous catalyst[29]. It is based on the concept of supra-molecular chemistry, and is able to oxidise methane 30 times better than other catalysts currently available and at lower temperatures (thus avoiding the increase in NOx and CO tailpipe emissions). This catalyst is based on Palladium (Pd) and Ceria (CeO_2), which improves the catalytic activity of supported Pd by stabilising PdO_x. However, pure CeO_2 has limited thermal stability, which results in the catalytic process becoming less efficient above certain temperatures. To overcome this issue, a team of researchers from the University of Pennsylvania, along with collaborators from Italy and Spain, has been able to reorganise Ceria at nanoscale to ensure that its molecules are evenly distributed. This avoids the deterioration of the material at high temperatures, resulting in a performance 30 times better, completely burning methane emissions at 400 C. Although this development offers exceptional opportunities, it still has some shortcomings in terms of withstanding deteriorations from other exhaust gases such as phosphorus,

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[24] http://ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=4380
[25] http://www.greencarcongress.com/2012/08/cargnello-20120813.html
[26] Low Emission HGV Task Force Recommendations on the use of methane and biomethane in HGVs
[27] http://ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=4380
[28] http://www.greencarcongress.com/2012/08/cargnello-20120813.html
[29] http://www.greencarcongress.com/2012/08/cargnello-20120813.html

zinc, and calcium; decreases in performance due to steam from lean-burn engines and the still relatively high cost.

3 Preliminary Methane Slip Test Protocol

3.1 Appropriate drive cycles and location of testing

3.1.1 Introduction to HGV testing

Euro emissions standards for heavy duty diesel engines came into effect in 1992, starting with Euro I[30]. These standards have increased in stringency over time. The early emission standards formed part of a Framework Directive, and were implemented via Regulations. The most recent standard is the Euro VI standard (Regulation 595/2009/EC). Among other major revisions, Euro VI has seen the introduction of off-cycle and in-use testing in an attempt to closer capture the real-world vehicle performance.

This section assesses the suitability of existing test protocols for the reliable measurement of emissions from natural gas-fuelled HDVs. When selecting the optimum existing cycle(s) for use in this test protocol, parameters to be evaluated include the following criteria:

- Suitability for measuring emissions (i) per kWh and (ii) per km;
- Cost;
- Availability of facilities and test equipment;
- Accuracy of results (repeatability and reproducibility);
- Relevance to real world driving conditions; and
- Correlation to existing type approval testing regulations.

What was sought was the most practical test cycle which encourages innovative emission reduction solutions yet maintains comparability to existing HDV standards. A summary of this study's review on drive cycles is given in Table 3-2 at the end of this section.

3.1.2 Testing strategies for HDVs: Regulatory testing

Heavy duty diesel emission standards were first adopted in July 1988[30]. Since this time, type approval has been performed on new engine designs before they are incorporated into HDVs. Consequently limit values have been expressed in units of grams per kilowatt-hour of useable work produced by the engine (g/kWh) rather than grams per kilometre (g/km) (the latter is used for measuring and regulating emissions from light duty vehicles). All current and historical engine tests are pass/fail, dependent on whether particular emissions over the entire test exceed specified limits (see Table 1-3). The engines are tested separately before they are built into vehicles. This is principally due to the high diversity of available vehicle configurations compared to the number of annual registrations and compared to the much smaller number of engine models that are used. Testing the engine directly promotes investment into advanced engine technologies, which otherwise may take many additional years to reach the market. A summary of the principal engine dynamometer and chassis dynamometer tests that are used for European regulatory purposes is given below, and described in more detail in Appendix 3.

3.1.2.1 Engine dynamometer tests

ECE R-49	A 13 mode steady state engine test used for Euro I and II type approval
ESC	European Static Cycle replaced the R-49 test in 2000. A revised 13 mode steady state engine test used for Euro III to V type approval.
ETC	European Transient Cycle augmented the ESC providing a transient, 30 minute duration engine test used for Euro III to V type approval.
ELR	European Load Response augmented the ESC and ETC. It provided an engine test used to check smoke emissions for Euro III to V type approval.

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[30] Introduced through Directive 88/77/EEC, amended in 1991 by 91/542/EEC.

WHSC	World Harmonised Static Cycle introduced for Euro VI type approval updating the ESC to better operation of heavy duty vehicles across the world. Again an engine test.
WHTC	World Harmonised Transient Cycle introduced for Euro VI type approval updating the ETC to better reflect normal operation of heavy duty vehicles across the world.

3.1.2.2 Chassis dynamometer tests

FIGE road cycle	Essentially a chassis version of the ETC engine test providing a transient, 30 minute duration driving test used with 10 minutes simulating urban, suburban and motorway driving.
WHVC	World Harmonised **Vehicle** Cycle, which is essentially a chassis version of the WHTC engine test providing a transient, 30 minute duration driving test simulating urban, suburban and motorway driving.

3.1.2.3 Computer simulation tools

VECTO cycles	Vehicle drive cycle “missions” under development by the European Commission as part of their plans to quantify HDV CO_2 emissions.

3.1.3 Portable Emissions Measurement System (PEMS) testing

Portable Emissions Measurement System (PEMS) testing was announced optionally under Euro V and became mandatory as part of the Euro VI in-service conformity testing which was introduced to counter excessive ‘off-cycle’ emissions. Testing must be performed within 1.5 years of type approval and repeated every two years over the life of an engine, until at least five years beyond its deployed service. The repeat tests ensure that catalyst degradation is accounted for, i.e. ‘in-service conformity’, and do not address ‘real world emissions’ specifically.

PEMS testing can be performed on a track or on the road and measures emissions from the entire vehicle. Emissions are performed on a per km basis, however conversion to a per kWh basis is possible[31]. The benefits of PEMS testing are numerous – vehicles of virtually any size and shape can be evaluated using the same equipment; it is relatively inexpensive in comparison to the engine and chassis dynamometer methods; it is able to measure emissions from hybrid and four-wheel drive vehicles which could require a very expensive dynamometer; it allows development work to be done ‘on-the-road’; it can be entirely representative of real-world driving; it can effectively prohibit gaming methods and it is possible (though, not for type approval purposes) to test the vehicle during its regular operation.

Annex II of Regulation 582/2011 explains the operational requirements for PEMS testing; the data is taken using 50-60% vehicle load from a single test outing (i.e. different outings cannot be ‘stitched’ together) and the emissions are averaged over a series of subsets within the entire run, named Moving Average Windows (MAWs). The duration of the test is dependent on engine power rather than a set time and is run “long enough to complete five times the work performed during the WHTC or produce five times the CO_2 reference mass in kg/cycle from the WHTC as applicable.” Each MAW over which the averaging is performed is equivalent to one such WHTC engine-work total, typically between 1000 and 2000 seconds (AVL, 2012). This MAW principle is used to maintain comparability with the laboratory tests.

PEMS testing is hot-start and emissions sampling cannot occur until the coolant temperature has reached 70°C or stabilised at ‘hot’. Measured trips must also contain prescribed proportions of driving conditions as summarised in Table 3-1, for which urban is defined as vehicle speeds between 0-50 km/h, rural is 50-75 km/h and motorway is >75 km/h. Compliance is demonstrated if the 90th cumulative percentile of all average emissions, in g/kWh, over each MAW do not exceed 1.5 times the WHTC test limit.

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[31] PEMS measurements are made in g/km and require conversion to g/kWh, the units of the type approval limits. The CO_2 emissions, which are already measured by the PEMS equipment in real-time, are directly related to the fuel burned which is itself a proxy for the work done, in kWh, by the engine. This is described more fully in section 5.

Table 3-1 - Required outing characteristics (±5%)

Vehicle Class	Urban %	Rural %	Motorway %
M_1, M_2 & M_3 (Class III) (Vehicles used to transport passengers) N_1, N_2 (Vehicles used to transport goods) with GVW ≤ 12,000 kg	45	25	30
M_2 & M_3 (Classes I & II), passenger vehicles carrying > 9 persons and GVW > 3,500 kg	70	30	-
N_3 (Vehicles used to transport goods) with GVW > 12,000 kg	20	25	55

Source: Adapted from EC Regulation 582/2011

The in-service conformity test monitors carbon monoxide (CO), THC[32], non-methane hydrocarbons[33] (NMHC), CH_4[34], NO_x, PM mass and PN, however does not provide pass-fail criteria for the latter two.

Besides the pollutant emissions, PEMS equipment must also log a number of other parameters to ensure each test can be compared like-for-like. These involve removing factors from external influences, including but not limited to:

- Ambient air temperature [K];
- Ambient pressure [kPa];
- Ambient humidity [g/kg] – not mandatory;
- Engine intake air temperature [K];
- Vehicle ground speed [km/h] from ECU and GPS;
- Vehicle altitude; and
- Vehicle latitude and longitude [degree] for route traceability purposes.

This forms what could perhaps be the main drawback of PEMS testing; variations in factors such as temperature, humidity, pressure, rainfall and traffic give cause for concern that the results could be less repeatable and less reproducible than laboratory testing. In addition, PEMS are limited by size, weight and power consumption and thus are not currently capable of the same accuracy as static, state of the art laboratory instrumentation. Laboratory comparison tests do, however, reveal close correlation between PEMS and chassis dynamometer readings. Some of the factors introducing variability can be minimised by the PEMS operator, such as by placing climate limits on testing and by using similar drivers to reduce behavioural effects. Track testing, rather than road testing, is able to further reduce some of the factors which can cause variability in the results, because simulation of traffic can be fully managed, routes can be guaranteed and stops (for instance at traffic lights) can be specified. When these optimisations are used, the PEMS team at Millbrook Proving Ground have achieved coefficients of variance frequently equal to or exceeding the level of repeatability seen in their chassis dynamometer laboratory.

A practical disadvantage of testing in the absence of a dynamometer is the constraint of being confined to road or track-defined engine loads. A dynamometer can sample all required points on an engine map very quickly, however road based testing can only sample conditions which the particular route is subject to. Engine testing can simulate both half and full load in the same test whereas road based testing would require a pause in testing, and a return to base, for changing of the trailer. For the purposes of this study, this limitation is relatively minor as its objective is to determine levels of methane slip from a broad perspective. However, further investigation would need to be done if a dedicated cycle were to be specified. Track-based testing can minimise this issue somewhat as it is possible to incorporate desired road gradients into the PEMS route which may otherwise not occur nearby the testing centre on the public roads and also remain close to the testing base. This ensures certain

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[32] Measured for all; limit applies only to compression-ignition engines.
[33] Measured for all; limit applies only to positive-ignition engines.
[34] Positive-ignition engines only.

torques are demanded from the engine during the test, sampling uncommon points of the engine map more frequently and potentially shortening the test. A restriction on track testing occurs for geographic locations that are some considerable distance from a suitable test track.

As with all measurement devices, the equipment requires careful calibration and set up. In particular for PEMS, it is imperative that the kit is correctly time-aligned to the vehicle ECU so that changes in engine conditions can be correlated with the corresponding change in emissions. Detectors and exhaust flow meter must also all be time-aligned to mitigate the bias associated with any time lag between them[35].

There are also regulatory issues with PEMS testing concerning the selection of an appropriate representative vehicle for the test. The parent engine (within a family of engines) is tested when situated in the most representative vehicle type it is used in. This means that it is often the case that engines used in buses are actually tested on haulage trucks, which evidently have very different operating conditions and especially average speeds. Given that this study is focusing on heavy goods vehicles, however, this does not present an issue for the selection of an appropriate testing strategy.

3.1.4 Unloaded testing

At the annual vehicle roadworthiness test (more commonly known as the MOT test) heavy duty vehicles emissions are cursorily assessed. This uses a free acceleration test, which is performed on the stationary vehicle. With the engine at idle, and the vehicle in neutral, the accelerator is completely depressed quickly, but not violently, such that the engine speed rises rapidly to reach the engine limited speed. The engine is under no load other than that of its own inertia, including its flywheel. The smoke emitted is monitored using a DVSA approved MOT smoke meter.

For vehicles equipped with old technology, with mechanical fuelling racks etc., and a direct link between the accelerator pedal and the fuel rack, this provides a check on the vehicle's fuelling system, the injectors, and that appropriate amounts of air were being fed to the engine. In modern vehicles with their computer controlled electronic fuel injection and myriad of sensors, the test is of much reduced value, and vehicles rarely fail.

In addition, for most dual-fuel vehicles methane substitution rates at idle are zero. Therefore overall unloaded testing has become discredited and although it is convenient, it is not recommended as a potential test protocol.

3.1.5 Summary matrix

Below is a brief summary matrix of the testing regimes:

Table 3-2 – Summary of different types of testing regimes against a range of criteria

	Regulatory / Engine testing	Chassis dynamometer / vehicle testing	PEMS with real driving	Unloaded testing
Suitability for measuring emissions (i) per kWh (ii) per km	Per kWh	Per km	Per km Per second Per kWh Per kgCO$_2$	Not suitable
Cost of testing	Very High	Very high	Moderate (~few £1,000s)	Very low
Availability of facilities and test equipment	Good	Very Poor	Poor	Good[36]

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[35] The procedure for time-alignment is dictated by section 9.3.5 of (UN ECE, 2014).

[36] For currently specified tests.

	Regulatory / Engine testing	Chassis dynamometer / vehicle testing	PEMS with real driving	Unloaded testing
Accuracy of results, covering repeatability and reproducibility	Very Good	Very Good	Good / Very Good	Fair / Poor
Relevance to real world driving conditions	Poor[37]	Good[38]	Very good	None
Correlation to existing type approval testing regulations	Very Good (identical)	Poor[39]	Fair	Very Poor
Notes	Promotes investment in engine technologies, but at the expense of other emission reduction technologies	Promotes investment in vehicle technologies	Captures real-world emissions and thus promotes investment into the most cost-effective technologies.	Pragmatic approach for annual road-worthiness emissions testing

3.2 PEMS equipment

3.2.1 Introduction - benefit and current regulations

As described in Section 3.1.3, the use of PEMS was introduced for Euro VI in order to address the growing difference between emissions performance as measured on the type approval test cycle and real-world emissions performance. As powertrain emissions capabilities are known to deteriorate with the time used, the PEMS equipment is used to conduct in-service conformity tests for HDV Euro VI compliant engines every two years.

The combination of in-service conformity and dedicated engine testing strategies are complementary. Whereas engine manufacturers are required to pass type approval of engines which will be used in HDV applications, the vehicle assembler is responsible for ensuring the entire vehicle conforms over its lifetime. Engine manufacturers are thus incentivised to produce engines with low emissions, and vehicle manufacturers must ensure after-treatment devices continue to perform.

3.2.2 Current PEMS capabilities

Portable emissions measurement systems are a relatively new technology to the automotive sector and evidently one of their greatest requirements is to closely match or exceed the repeatability of the current static equipment used in conjunction with dynamometers. Discussions with PEMS experts at Millbrook Proving Ground revealed track testing repeatability (quantified by the standard deviation over multiple tests) to be as good as or better than levels of repeatability seen on the dynamometers, which themselves are typically give <1.0% variation in measured results for CO_2 emissions, for instance.

It is also important that the PEMS gives accurate readings which closely match the dynamometer equipment. Millbrook's most recent correlation study achieved CO_2 measurements well within the industry accepted variance limit of 5% between the two systems. Occasionally larger systematic differences have been noted. These have originated from the exhaust flow meter being used outside

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[37] Lack of gearbox makes it difficult to translate between the two; test cycles do not reflect real-world driving.
[38] Cycle dependent.
[39] Per km basis.

its linear region. Whilst this affects absolute emissions measurement it introduces virtually the same error into measurements for both a methane vehicle and its diesel comparator. Consequently it introduces only a small error into the quantification of the changes in GHG emission for this protocol.

Measurement of the following parameters outlined in Table 3-3 is required for Euro VI in-service conformity tests via a PEMS device. This table is Table 1 of Appendix 1 to Annex II (Conformity of in-service engines or vehicle) of Regulation (EC) 582/2011.

Table 3-3: Test parameters requiring instantaneous measurement by PEMS unit

Parameter	Unit	Measurement Device
CH_4 concentration[1]	Ppm	Analyser
CO concentration	Ppm	Analyser
CO_2 concentration	Ppm	Analyser
NO_x concentration	Ppm	Analyser
THC concentration	Ppm	Analyser
Exhaust gas flow	kg/h	Exhaust flow meter
Exhaust temperature	Kelvin (K)	Exhaust flow temperature sensor
Ambient temperature	Kelvin (K)	Sensor
Ambient pressure	kPa	Sensor
Engine torque	Nm	ECU or sensor
Engine speed	Rpm	ECU or sensor
Engine fuel flow	g/second	ECU or sensor
Engine coolant temperature	K	ECU or sensor
Engine intake air temperature	K	Sensor
Vehicle ground speed	km/h	ECU and GPS
Vehicle latitude	degree	GPS
Vehicle longitude	degree	GPS

Notes:

[1] Positive ignition-engines only.

Source: EC Regulation 582/2011/EC (EC, 2011)

3.2.3 Methods of analysis

The analytical techniques used in standard PEMS equipment are detailed in Appendix 4.

The critical question regarding PEMS equipment and this project is: “Whether PEMS can measure CH_4 and CO_2 accurately?”

3.2.3.1 CH_4 and THC analysis

Standard PEMS equipment is required to measure total hydrocarbons (THC). This is achieved using a flame ionisation detector (FID), the same analysis technique that is specified for type approval testing.

A methane cutter can be added, but many PEMS systems do not have this additional option. This is an oxidation catalyst whose principle of operation is shown in Figure 2-4 which shows how higher temperatures are required to oxidise methane relative to other hydrocarbons. A temperature is selected that leads to the oxidation of virtually all other hydrocarbons in the exhaust gases, except methane. The output from this catalyst, containing the unreacted methane but virtually no other hydrocarbons is then analysed by a FID. Hence the FID signal from the methane cutter is the concentration of methane, whilst the FID signal from the untreated gas stream is the concentration of total hydrocarbons.

Table 1-3 gives the type approval limit values for the non-methane THC emissions from Euro V vehicles as 0.55 g/kWh and the THC emissions from Euro VI vehicles as 0.16 g/kWh. Testing carried out for this project, and described more fully in Chapter 4, estimated THC from a dual fuel Euro V vehicle when operating in diesel-only mode of around 0.27 g/kWh (0.11 g/km). This is around 50% of the type approval limit. The conclusion from the type approval limits, the data measured in this study, and the generally agreed THC emission factors for HDV, is that **THC emissions from diesel-only operations are very low**. The consequence of this is that if a THC analyser is used for a dual fuelled HDV the non-methane component is small, and taking the THC signal as a proxy for methane emissions is reasonable[40].

For dedicated methane vehicles there are also very low non-methane hydrocarbon emissions. Not least because heavier hydrocarbons are difficult to synthesise in the combustion chamber starting from methane, and contributions from lube oil etc. are very small.

It is therefore concluded that if a PEMS has a methane cutter, and can measure methane concentrations separately, this is ideal. However, if a PEMS can only measure THC then for both dual fuelled and dedicated methane vehicles this is a sufficiently good proxy for the methane measurement that it would enable the methane emissions to be appropriately quantified.

3.2.3.2 Carbon dioxide CO_2 analysis

The accurate measurement of the change in GHG emissions from the use of methane as a fuel in HDVs, arises from both the impact of methane emissions and the change in their CO_2 emissions relative to a comparator diesel only fuelled vehicle. Consequently suitable PEMS need to accurately measure CO_2 emissions too.

Carbon monoxide (CO) and carbon dioxide (CO_2) emissions are generally measured by PEMS using non-dispersive infrared absorption spectroscopy (NDIR). NDIR analysers provide effective measurement with high stability, fast response times, long lifetimes and at a relatively low cost. Therefore a standard PEMS can analyse CO_2 emissions to the desired accuracy. For further details on NDIR analysis see Appendix 4.

3.2.4 Examples in the marketplace

Although there are a number of PEMS suppliers, particularly those producing modular analysers for specific emissions[41], it is considered[42] that there are currently three main competitors in the UK automotive sector offering comprehensive PEMS packages. In alphabetical order, these are AVL, Horiba and Sensors, Inc. Each company produces emissions systems compliant with the UN ECE R-49, EC Regulation 582/2011 and 40CFR part 1065 legislation; each is currently in use at major automotive testing facilities in the UK. The principal feature of PEMS-specific capabilities are summarised in Table 3-4. A more detailed version of this table is provided in Appendix 4.

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[40] Using the GWP of methane as 28, if the THC emissions measured, 0.111 g/km, is taken as methane this is equivalent to an additional 3 g/km CO_2 emissions. In the context of the actual CO_2 emissions, 820 g/km, this introduces an "error" of 0.36%. This is adjudged to be a small, systematic and acceptable error.

[41] Especially particulate counting – 3DatX, Matter Aerosol and Pegasor for example.

[42] This became clear after discussions with various UK-based PEMS operators.

Table 3-4: PEMS unit capabilities from three major manufacturers.

Parameter	AVL	Horiba (OBS-ONE-GS11 and GS12)	Sensors, Inc. SEMTECH ECOSTAR (EFM 2)
CH_4	N/A	N/A	Dual FID (0-100 to 0-40000ppmC)
CO	NDIR (0–5% vol.)	Heated NDIR (0-0.5 to 0-10% vol.)	NDIR (0-8.5% vol.)
CO_2	NDIR (0–20% vol.)	Heated NDIR (0-5 to 0-20% vol.)	NDIR (0-18% vol.)
NO	NDUV (0–5000ppm)	Heated-dual CLD (0-100 to 0-3000ppm)	NDUV (0-3000ppm)
NO_2	NDUV (0–2500ppm)	Heated-dual CLD (0-100 to 0-3000ppm)	NDUV (0-500ppm)
O_2	Electrochemical	N/A	Electrochemical or paramagnetic
PM	Options available	Options available	Options available
PN	Photo-acoustic detector (≤10µg/m^3)	✓	Ion mobility technique analyser
THC	Heated FID (0–30000ppmC)	Heated FID (0-100 to 0-10000ppmC)	Heated FID (0-90ppm to 0-30000ppm) or NDIR
Exhaust flow meter	Pitot flow meter	Pitot flow meter (0-2.0 to 0-65.0 m^3/min)	✓
Flow tube max flow rate[a] (m^3/min), @flow tube diameter	-	17 @3” 31 @3.5” 48 @4”	20 @3” 25 @4” 30 @5”
Exhaust temperature	✓	✓	✓
Operating conditions	-30 to 45°C	-10 to 45°C	-10 to 45°C

Notes to Table 3-4.

[a] At 25mbar backpressure, 200°C exhaust temperature.

Source: Manufacturer websites and associated brochures as of November 2014. This list is compiled from multiple sources and may not be complete.

3.2.5 Potential issues with PEMS for methane slip application

HDV PEMS testing is just emerging from its infancy and the technology is developing rapidly. Following work in the USA, the European Commission began consulting with HDV manufacturers in 2004, culminating in a 2006-2008 pilot programme which assessed the technical and administrative aspects of PEMS. The EU-PEMS (JRC) programme then sought to determine whether the technological progress of PEMS instrumentation was sufficient for an imminent legislative introduction. Having concluded in late 2012 that the equipment was satisfactory, this voluntary programme led to the EU-PEMS PM Pilot Programme[43] which focused on the difficulties of PM measurement (Rubino, Bonnel, Carriero, & Krasenbrink, 2010), and then the EU-PEMS PN programme for particle counting. Recent assessments of the Euro VI in-service conformity procedures and the JRC's long-term plans to progress the use of PEMS from in-service conformity to a primary evaluation role (Vlachos, et al., 2014) demonstrate that the technology is still being refined and developed. In addition, the development rate is likely to be accelerated given its probable introduction for emissions testing of light duty vehicles[44]. Even with this developmental drive, PEMS systems are stretched to the edge of their capabilities. Simultaneous progress in engine and after-treatment technologies will require equipment with increased accuracy and precision as the quantities of measurement become smaller. This may generate frequent and significant costs for testing centres and may form part of the reason for the current limited availability of PEMS testing in Europe.

A further problem in transient testing arises from the time and distance lags associated with the positioning of the exhaust gas sampling points, located downstream of the engine. Mathematical techniques are used for reconstructing the true signal from the instrument signal, taking into account sampling delays and instrument response characteristics[45].

Future precision requirements also concern measurement of the methane slip. As argued above, proxy methods for detection of methane will be challenging at the Euro VI emission levels and may require relatively inexpensive measurement strategies to be employed. However, for this methane slip project, where the levels of methane emissions are many times the regulatory limits before the typical reductions in CO_2 emissions are negated by methane slip, then PEMS appears to be a cost effective, and proportionate, vehicle exhaust emissions characterisation technique.

3.3 Comparator vehicles

The purpose of comparator vehicles is to provide a baseline against which the change in CO_2 emissions can be accurately measured from a vehicle operating when fuelled with methane when compared to a diesel only fuelled equivalent. It also provides a baseline for methane, and total hydrocarbon, emissions against which the emissions from methane-fuelled vehicles can be compared.

For diesel dual-fuel (DDF) vehicles, it is was originally preferred that the single fuel diesel equivalent vehicles are viewed as the comparator vehicles rather than the DDF running on diesel only. This is because it has been reported that there can be issues about performance of the latter when running on pure diesel. Also, from a pragmatic perspective, there is a vast amount of data collected characterising the emissions from standard diesel trucks, rather than from dual-fuel vehicles running on diesel. Consequently this data will be more representative. However, the requirements of accurately measuring changes in both the CO_2 emissions and the methane emissions make the back to back testing of the same vehicle with the same load/trailer tested on the same or next day, overall a more accurate comparison for a specific vehicle. It is acknowledged that the vehicle tested may not be typical of the vehicle type or fleet as a whole. The emissions measured can be compared with the "average emission factors" described below.

For dedicated methane vehicles it is not possible to test the same vehicle in a methane and diesel only mode as their methane engines cannot run on diesel fuel. Therefore, a comparator diesel vehicle needs to be identified, and comparable data obtained. This was the approach adopted in the "Coca-Cola Enterprises biomethane vehicle trial"[46], where two different vehicles were tested side by side. Alternatively the emissions of the dedicated methane vehicle could be compared with the "average emission factors" given in the emission factor handbooks.

The methane, total hydrocarbon, and CO_2 emissions for average diesel HGVs are well characterised, and are used in the standard Tier 3 emissions inventory compilation methodology where vehicles are highly disaggregated according to size and their technology. There are 153 different types of trucks, buses and coaches listed. When this is combined with data for three different loading levels, seven

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[43] **Invalid source specified.**

[44] See EC Regulation 715/2007; anticipated by industry experts, e.g. **Invalid source specified.**.

[45] *Beaumont 1990]*. - https://www.dieselnet.com/tech/measure_gas.php

[46] For report on the Cenex Coca-Cola Enterprises biomethane vehicle trial see http://www.cenex.co.uk/wp-content/uploads/2014/02/CCE-biomethane-trial-report-1_3.pdf

gradients, and the other four pollutants listed, this leads to a database of 16,065 different speed-related emission factors. However, it should be remembered that these data are expressed in g/km. These data are not directly comparable to the type approval emission values, which are expressed in g/kWh.

The speed-related emission factors are expressed in terms of the coefficients of a speed polynomial, so that emission factors for different speeds can be estimated. The data given in the EMEP/EEA air pollutant emissions inventory guidebook (2013) are the same for THC as the COPERT 4 v11 speed related emission functions[47]. When these are used for illustrative rigid and articulated trucks, the **total hydrocarbon emission factors** and fuel consumption data are as given in Table 3-5.

Table 3-5: Vehicle category-drive cycle combinations currently available for simulation runs in VECTO

Vehicle category	Drive cycles/emissions		
	THC (g/km)	Fuel consumption (g/km)	THC / 200 g fuel
Rigid truck,14 – 20 t GVW, 45 km/h, 50% load, level road			
Euro V EGR NOx control	0.039	185.3	42 mg
Euro V SCR NOx control	0.020	178.5	22 mg
Articulated truck, 34 – 40 t GVW, 75 km/h, 50% load, level road			
Euro V EGR NOx control	0.042	232.2	36 mg
Euro V SCR NOx control	0.020	221.8	18 mg

Source: EEA, 2013

The figures given in Table 3-5 are for Euro V vehicles which use EGR and SCR NOx control systems. Data for Euro VI vehicles are derived from these Euro V factors at present, there being insufficient data to derive independent values.

An indicative emission factor per kWh can be estimated for direct comparison to the type approval limits. The work produced by engines/vehicles is a direct consequence of combusting fuel. A useful generalisation is that 1 kWh of work is produced from a heavy duty truck engine for each 200g of fuel consumed (this may vary by up to 10% according to engine efficiency and the duty cycle). Using this proxy for kWh, during normal operation Euro V trucks using EGR NOx control produce around 30 – 50 mg THC/kWh and Euro V trucks using SCR NOx control produce around 12 – 28 mg THC/kWh. All of these values are significantly below the 550 mg/kWh for Euro V and 160 mg/kWh for Euro VI engine limits for heavy duty vehicles.

The EMEP/EEA air pollutant emissions inventory guidebook (EEA, 2013) also provides data for the hydrocarbon speciation. Table 3-72 within the guidebook provides methane emission factors of 175 – 70 mg/km for heavy duty diesel vehicles (the key portions of this table referring to HGVs is given in Table 2-4 of this report). However, these are average figures often coming from studies originally carried out in the early 1990s, and data are not quoted for the different Euro standards.

However, Table 3.73 indicates that relative to Euro I HDV engines, the methane emissions for Euro IV and later technologies are reduced by 97%, i.e. are only 3% of the Euro I, which applied to all HDVs registered after 1993. The key portions of this table referring to HDVs is given in Appendix 2 of this report.

Table 3.112a of the EMEP/EEA guide book gives data for petrol vehicles and HDV (EEA, 2013). For petrol vehicles the first few alkanes, up to hexane, comprise 21% of the NMVOCs. For HDD engines the figure is just under 0.5%. The key portions of this table referring to HDVs is given in Appendix 2 of this report.

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[47] **COPERT 4** is a software tool used world-wide to calculate air pollutant and greenhouse gas emissions from road transport. The development of COPERT is coordinated by the European Environment Agency (EEA) and the European Commission's Joint Research Centre manages the scientific development of the model. The COPERT 4 methodology is part of the EMEP/EEA air pollutant emission inventory guidebook for the calculation of air pollutant emissions and is consistent with the 2006 IPCC Guidelines for the calculation of greenhouse gas emissions.

All this evidence suggests that:

- Total hydrocarbon emissions from modern, Euro V and later, heavy duty diesel engines, under diesel-only operation, are low - less than 250 mg/km or 50 mg/kWh; and
- Methane emissions are a small fraction of this (<10%), i.e. less than 25 mg/km or 5 mg/kWh.

3.4 Fuel quality – types of methane fuel

Whilst methane is a well-defined chemical compound, CH_4, the more generic title of “methane fuels” encompasses several aspects:

- The origin of the methane;
- The physical form of the fuel; and
- The chemical composition of the fuel.

There are two principal sources of methane: fossil methane from gas fields and bio-methane, formed from organic material. The latter is often made in an anaerobic digester, which produces bio-gas, a mixture of methane, nitrogen, carbon dioxide and other more minor components. To turn this bio-gas into bio-methane that can be used in vehicles requires a clean-up process. In terms of their use as vehicle fuels, fossil methane and bio-methane are equivalent to each other, and no differentiation between them is made in this study. However, in terms of climate change impacts fossil methane and bio-methane are **very different**, with bio-methane either being viewed as a renewable resource, or even more positively where its use as a fuel, and conversion to carbon dioxide and water releases much lower levels of GHGs than fossil methane.

Methane is a gas at ambient temperatures. Unlike LPG (propane and butane) it cannot be liquefied by pressure alone at ambient temperatures. Therefore on a vehicle it is either stored as compressed gas (for use in compressed natural gas (CNG) fuelled vehicles) or as a cryogenic liquid in specially constructed cryogenic pressure vessels (for use in liquefied natural gas (LNG) fuelled vehicles). With regard to methane slip contributing to tail-pipe emissions, consultations have indicated that there is no difference between CNG and LNG fuelled vehicles (or their bio-methane analogues using CBM and LBM). Therefore, no differentiation is made in this study between compressed and liquefied fuels.

The chemical composition of methane is unequivocal, unlike petrol or diesel which are a complex mixture of compounds. However, “methane fuels” is a term used for fuels where a majority of the energy content is in the form of methane. This can apply to mixtures whose methane content varies from 100% to close to 80%. The energy content and combustion characteristics between these two extremes varies markedly. This also markedly influences methane slip.

For petrol and diesel there are standard fuel specifications (e.g. EN 228 for petrol and EN 590 for diesel). There is currently no equivalent standard for methane fuels.

Annex IX of Regulation 582/2011 does provide technical data and specifications for reference fuels. This gives data for three different reference fuels, as tabulated in Table 3-6.

Table 3-6: Characteristics of reference fuels G_R, G_{23} and G_{25}

Parameter	G_R	G_{23}	G_{25}
Methane content	84% - 89% (87%)	91.5% - 93.5% (92.5%)	84% - 88% (86%)
Ethane content	11% - 15% (13%)	-	-
Balance	0 – 1% mole	0 – 1% mole	No
Nitrogen content	-	6.5% - 8.5% (7.5%)	12% - 16% (14%)
Sulphur content	Max 10 mg/m³	Max 10 mg/m³	Max 10 mg/m³

Source: EC, 2011

G_{20} is used to denote pure methane.

These contain increasing amounts of inert (non-combustible, as in nitrogen) material. The reference fuel GR contains >99% of hydrocarbon, with between 84% - 89% methane and most of the balance ethane.

Annex I of Regulation EC 582/2011 gives administrative provisions for EC Type-Approval. It specifies requirements on the fuel range, as shown in Box 3.

Box 3: Part of Annex I (Administrative provisions for EC type-approval) from Regulation EC 582/2011 (EC, 2011)

> 1.1.3 In the case of a natural gas fuelled engine the manufacturer shall demonstrate the parent engines capability to adapt to any fuel composition that may occur on the market within the European Union.
>
> In the case of natural gas there are generally two types of fuel, high calorific fuel (H-gas) and low calorific fuel (L-gas), but with a significant spread within both ranges; they differ significantly in their energy content expressed by the Wobbe Index and in their λ-shift factor (S_λ). Natural gases with a λ-shift factor between 0.89 and 1.08 are considered to belong to the H-range.

However, there is evidence that methane slip does vary markedly with fuel quality. The following two slides were kindly provided by (and are used here with the permission of) B McMurray (a consultant trading as LambdaX) and were shared with the SMMT Methane Task Force, a sub-group of the SMMT Fuels Working Group. These show that relative to UK pipeline natural gas, pure methane (G20) leads to a reduction in THC emissions, whereas increasing amounts of inert diluent, G23 with 7% nitrogen, and G25 with 14% nitrogen lead to approximately a doubling and tripling of the THC emissions when the emissions are not corrected for cycle work, and still more than a doubling when they are corrected for cycle work.

Figure 3-1: NG calibration gases evaluation on ESC uncorrected for cycle work

	% Cycle NOx	% Cycle THC	% Cycle Work
BASELINE UK PIPELINE	0	0	0
G20 100% CH4	-7	-9	0
G23 93% CH4 / 7% N2	-28	96	-22
G25 86% CH4 / 14% N2	-36	190	-36
GR 87% CH4 / 13% C2H6	18	-18	14

Figure 3-2: NG calibration gases evaluation on ESC corrected for cycle work

	% Cycle NOx	% Cycle THC	% Cycle Work
BASELINE UK PIPELINE	0	0	0
G20 100% CH4	-7	-9	0
G23 93% CH4 / 7% N2	-6	71	0
G25 86% CH4 / 14% N2	-18	109	0
GR 87% CH4 / 13% C2H6	13	-10	0

Source of both figures: LambdaX, 2014

This implies that measuring methane (or hydrocarbon) slip without knowing what fuel is being used devalues the results.

3.5 Reliability of testing

The reliability of testing is not dependent on a single factor, rather it varies according to:

a. The size of the parameter to be measured;

b. The accuracy with which the parameter can be measured by the analysis technique;

c. The accuracy with which other parameters required in the data processing can be measured by their analysis techniques;

d. The variability of the parameter of interest with uncontrolled aspects of the test protocol;

e. The size and variability of any background interfering signal; and

f. The accuracy required for the measurement of the parameter of interest.

This application seeks to measure the change in GHG emissions. This can be expressed as:

Δ GHG emissions = Δ CO_2 emissions + Δ Methane emissions * GWP (methane, i.e. 28)

Where Δ Species = Concentration of species from the methane fuelled HDV

less the concentration of species from diesel only fuelled comparator HDV.

Therefore, two species need to measured, methane emissions and CO_2 emissions.

3.5.1 Reliability of methane emissions measurements:

a. The size of the signal to be measured is the amount of methane emissions that would negate the GHG emissions reduction caused by lower CO_2 emissions. Typically CO_2 emissions are around 800 g/km. The Low Carbon Truck Trial Year 1 report indicates average substitution ratio[48] is around 46%, and CO_2 emissions savings are 9% (72 g/km). A methane slip of **2.6 g/km** would be equivalent to a further 72.8 g CO_2/km (100 year GWP for methane taken as 28).

b. FIDs are highly sensitive and accurate and are able to measure HC emissions for an engine cycle to better than ± 10% of the around 40 mg cycle emissions, i.e. error is less than 4 mg methane, or 0.004 g/km.

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[48] In the First Annual Report the substitution ratio is defined as “the percentage of diesel fuel replaced by gas”.

c. However, for PEMS to measure the methane emissions flux requires measuring both methane/hydrocarbon concentration and exhaust flow rate. This might reduce the accuracy to give an error of less than 6 mg/km methane.

   In addition, if the data processing requires normalising with respect to CO_2 emissions as a proxy to convert into mg/kWh, errors in measuring this also need to be considered. This could increase the error by a factor of √2 to less than ±6 mg methane/kWh.

d. The variability of methane slip with the uncontrolled variability of the test protocol, i.e. the reproducibility of the test cycle with road and weather conditions is not known. This will be returned to later.

e. The size and variability of any background interfering signal arises principally from the background hydrocarbon emissions from comparator vehicles. It was estimated, using COPERT 4 v11 speed related emission factors for heavy duty vehicles that this would be in the range 0.03 – 0.05 g NMHC/kWh. This would be 1.9% of a 2.6 g/kWh methane slip signal. This signal is not all a random error; it comprises a constant value, virtually always present and a cycle to cycle variable component, i.e. it is negligible.

f. The accuracy required for the measurement of the parameter of interest has yet to be determined.

When these sources of error and uncertainty are combined, it appears that factors b, c and e are less than ±0.075 g/kW. This is less than 3% of the amount of methane slip that would lead to the cancelling of the GHG emissions reduction caused by the average reduction in CO_2 emissions, before taking into account factor d.

Overall the concentration of methane from diesel only fuelled comparator HDV is essentially zero. Further, taking THC measurements from the methane fuelled HDV as a proxy for the change in methane concentration will introduce a small systematic error (overestimation) of around 3g CO_2e (or 0.36%) (see Section 3.2.3). The next section will show this is relatively small in the context of the reliability of the measurement of the change in CO_2 emissions.

3.5.2 Reliability of carbon dioxide emissions measurements

Measurement of the change in carbon dioxide (CO_2) emissions involves quantifying the CO_2 emissions from the methane fuelled HDV and from the diesel only fuelled comparator HDV. Section 4.4 reports on the reliability of testing from the practical phase of this study, and Table 4-20 and Table 4-21 reports that the standard deviation of the CO_2 measurements was ± 0.89% of the CO_2 emissions for the dedicated methane vehicle and ± 0.03% of the CO_2 emissions for the dual fuelled vehicle. In practice an uncertainty of ± 0.6% to ± 1.0% is generally achieved when:

- Triplicate measurements are made;
- Using the same vehicle;
- Driven over the same driving cycle;
- Measured using the same track/road;
- Using the same PEMS kit and the same installations;
- Tested by the same team;
- For measurements made relatively close together (same or consecutive days);
- When testing occurs for approximately the same weather conditions; and
- And the testing occurs for with the same load conditions.

Under these conditions the measurement of the change in CO_2 emissions between the methane vehicle and its diesel comparator would be ± 0.85% to ± 1.41% (√2 times the individual measurements).

This uncertainty will increase if items listed above change between the two sets of measurements. One important consequence of this is that whilst it was originally preferred that the single fuel diesel equivalent vehicles are viewed as the comparator vehicles rather than the DDF running on diesel only, this introduces additional measurement variability. To accurately measure changes in the CO_2 emissions the back to back testing of the same dual fuel vehicle with the same load/trailer tested on the same or next day is required with the vehicle fuelled alternately with diesel only and diesel/methane fuels.

3.5.3 Other factors influencing reliability of measurements

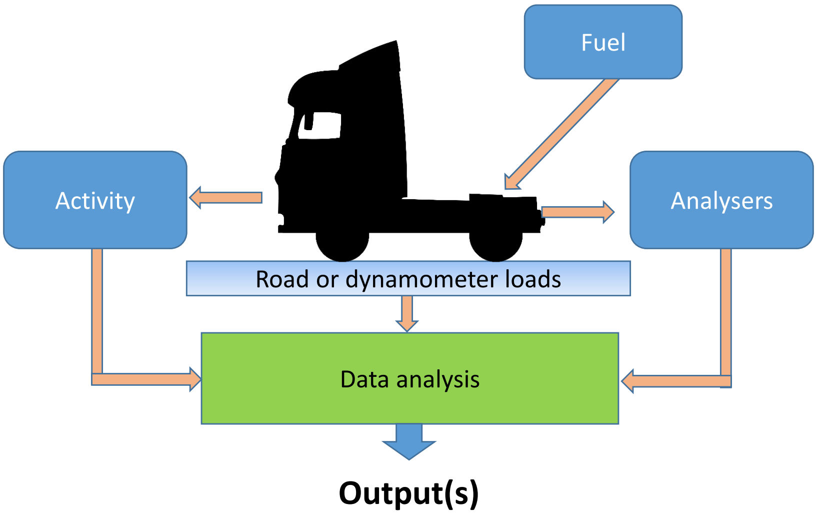
There are also other factors to be taken into consideration when considering the reliability of testing, and from this the number of repeat tests that would be required to ensure a robust measurement:

1. Fitting PEMS equipment to a heavy duty vehicle is not simply a matter of clipping it on to an exhaust pipe, as is the case for a smoke meter used in an MOT FAS test. It requires more time (and potentially some minor modifications to the vehicle exhaust system). Therefore, having made that time investment, it makes sense to undertake a proportionate amount of testing, and not conduct tests that have a duration of only a few seconds.
2. The PEMS signal is measured at a frequency of 1 Hz. Therefore, for a 10 minute drive cycle there is not a single bag measurement as is the case for the ECE portion of an NEDC light duty vehicle type approval test, but 600 data points. Intelligent processing of these would greatly improve the confidence in the answer for this single drive cycle relative to a single point measurement.

3.6 Preliminary test protocol for pilot vehicle testing

At this point in the project some clear, evidence-based recommendations were made regarding the test protocol to be used in the pilot vehicle testing phase of this study. The results of the testing, as well as a stakeholder engagement exercise, were subsequently used to produce a recommended final protocol, as described later, in Chapter 6 of this report.

Figure 3-3: Schematic of test framework



Source: Ricardo-AEA

1. The vehicle

Tests to be performed on whole vehicles, loaded with 50 – 60% of their maximum payload (consistent with Annex II of Regulation 582/2011/EC which sets out the requirements for PEMS testing). It is also consistent with levels of lading in the UK as estimated by UK Freight Transport Statistics (RSF0117) which estimate the average loading factor is between 40-60% of the maximum.

2. Its fuel

The diesel in the dual-fuelled vehicle should conform to EN 590, and the methane and ethane content of the gaseous fuel should be known.

3. Whether it is driven on a road or uses a dynamometer (or indeed involves engine testing)

Pilot testing to be undertaken by driving on a test track and on a chassis dynamometer to obtain comparative data for the two approaches. Assuming the two approached give essentially equivalent results, the aim would be to use test tracks testing for the building of an evidence base on methane emissions from vehicles under real operating conditions.

Engine or unloaded testing protocols are impractical for the evaluation of methane slip for vehicles when in use.

4. The driving cycle(s)

The current PEMS regulations and advice from a number of consultations is that the driving cycles should reflect all three segments of test cycles (urban, rural and motorway). The pilot testing should make use of the World Harmonised Vehicle Cycle (WHVC).

It is apparent from the literature survey undertaken and from the data coming from the Low Carbon Truck Trial that methane slip emissions vary with the different vehicle segments, but are clearly measurable for all speeds. This gives something of a resilience to the test, indicating that it does not have to focus on a specific, narrow region of the engine’s map, but give an indication of methane slip throughout the driving range.

5. The analysers to be used

The emissions produced during on track testing are to be analysed using PEMS equipment. Broadly this should be consistent with the PEMS specification in Annex II of Regulation 582/2011/EC. Methane should be measured using FID, and because the THC slip/emissions from comparator vehicles is relatively low, therefore a Total Hydrocarbon (THC) detector is adequate.

It is noted that this recommendation does not exclude any of the three main current types of PEMS systems available, and keeps the protocol consistent with the type approval regulations.

This is a pragmatic solution based on currently available PEMS equipment. However, it was also noted that methane sensors are becoming available, and potentially more affordable. In the future it may be that a methane sensor becomes increasingly practical. .

The testing should also measure pollutant emissions wherever possible, including NO_x, CO and PM, and, of course, CO_2.

6. The subsequent data analysis

The primary output from the data analysis will be THC emissions either in terms of per second, or per km. Whilst the earlier recommendations describe vehicle testing, the vehicle may weigh from around 4 tonnes (for a semi-loaded 7.5 t GVW rigid) to seven times this (for a semi-loaded 44 t GVW articulated truck). To account for this, and to align the results better with the g/kWh limits from type approval, it is recommended that the THC emissions are referenced to tailpipe CO_2 emissions.

All emissions (GHG and pollutant) to be analysed on a g/km basis.

7. Other aspects of the pilot testing protocol

Pilot testing conditions should be consistent with relevant sections of the PEMS specification in Annex II of Regulation 582/2011/EC. Specifically with regard to:

- Ambient conditions, pressure > 82.5 kPa; temperature > -7 C;
- Engine coolant temperature; and
- Exhaust temperatures.

Part of the current petrol vehicle MOT test involves checking catalyst function. Before a vehicle can be deemed to fail the test its operating temperature has to be its “normal running temperature”. For a stationary vehicle this is done using the engine’s oil temperature. For a vehicle driving on the road it is anticipated that measuring engine coolant and tail-pipe exhaust temperature will be sufficient.

For pilot testing of an articulated vehicle, the tractor unit should be coupled to a curtain-sided semi-trailer of the type commonly used in the UK.

4 Vehicle testing

4.1 Overview

4.1.1 Introduction

The objectives of the vehicle testing portion of the project was:

- To test both a dual fuel and a dedicated methane vehicle;
- To undertake a pilot test of the proposed test protocol;
- To gather additional information regarding key parameters involved, including the impact of the methane slip catalyst; and
- To undertake some more research-based testing to gather further evidence to support (and refine) the proposed test protocol regarding test equipment, driving procedure.

To achieve these objectives, two vehicles were hired. An Iveco Stralis, 26 tonne dedicated methane fuelled rigid truck and a demonstrator 40t Dual-fuel tractor unit which had been converted to run on diesel/liquefied natural gas (LNG). This vehicle was fitted with a relatively old methane slip catalyst, which could be removed and replaced with the original inactive, blank piece of exhaust. It was used with a semitrailer, a standard height curtain-sider, loaded with concrete blocks to achieve the target overall vehicle weight.

When analysing the data key questions addressed, as guided by the task's objectives, were:

1. What was the change in CO_2 emissions relative to the comparator vehicle?
2. What level of methane slip occurred?
3. How does the level of methane slip vary with key test and vehicle parameters (e.g. speed, loading, gas substitution ratio for dual fuel vehicles?
4. What is the difference between measuring THC and methane?
5. What is the impact of the catalyst?
6. What is the consequence on the design and robustness of the proposed test protocol?

4.1.2 Overview of the testing completed

The steps in the test programme followed were:

i. Receive vehicle, instrument and prepare for testing;
ii. Chassis dynamometer testing;
iii. On-road testing with PEMS; and
iv. Remove instrumentation and return vehicle.

The dedicated methane truck was tested at a single load, with around 50% payload, as this is consistent with the testing requirements for vehicles laid out in Regulation 582/2011/EC, and this is within the chassis dynamometer's range.

The dual-fuel vehicle was tested at two loads: lightly loaded, i.e. 20 tonnes for chassis dynamometer testing (because of dynamometer load restrictions) and heavily loaded, i.e. 30 tonnes. This higher figure corresponds to around 50% payload, and is consistent with the testing requirements for vehicles laid out in Regulation 582/2011/EC. An overview of the testing programme is given in Table 4-1.

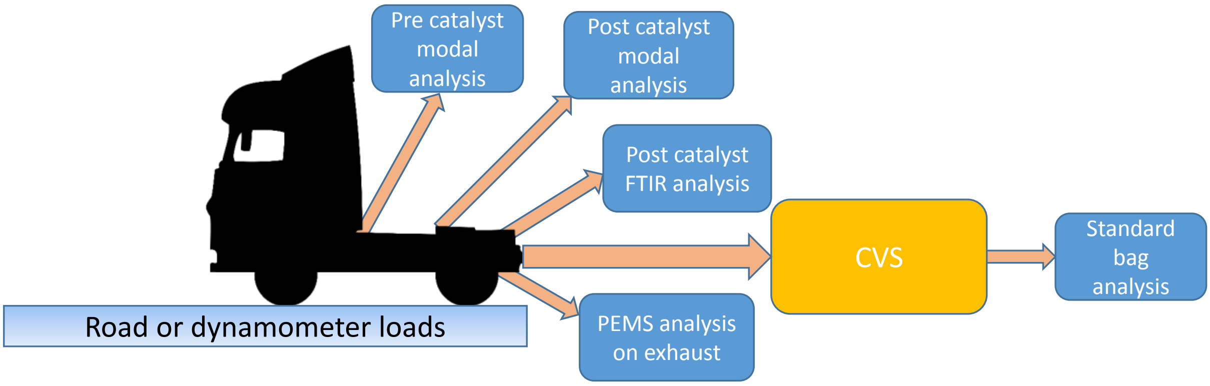
Table 4-1: Overview of testing programme

Testing	Dedicated methane vehicle		Dual fuel vehicle			
	Around 50% loaded (7.5t vehicle)		Lightly loaded (20t vehicle weight)		Heavily loaded (30t vehicle weight)	
	Tailpipe, after-catalyst	Pre-catalyst	Tailpipe, after-catalyst	Pre-catalyst	With catalyst	Without catalyst
Chassis dyno testing	✓	✓	✓	✓		
Track PEMS testing	✓				✓	✓

For both vehicles on the chassis dynamometer modal emissions measurements were made pre- and post-catalyst. Also regulatory bag analyses was undertaken and the PEMS equipment also sampled the tailpipe emissions. In addition, Fourier Transform Infra-red (FTIR) analysis was undertaken. This could be used to analyse emissions either pre or post-catalyst.

This is shown schematically in Figure 4-1.

Figure 4-1: Schematic of dynamometer tests



The modal analysis undertaken for chassis dynamometer testing includes analysis of:

- **Pre-methane catalyst** – total hydrocarbons (THC), CO, NOx, and CO_2
- **Post-methane catalyst** – total hydrocarbons (THC), CO, NOx, and CO_2 and PM by regulated filter.

The FTIR analysis provides analysis of methane, CO, NOx, NO, NO_2 and CO_2.

Fuel consumption was measured using the Regulated Carbon Balance Method for the dedicated methane truck.

For the dual-fuel truck, a diesel fuel flow meter was fitted. The methane fuel consumption was back calculated from the carbon balance equation after taking account of diesel consumption. Millbrook has found this approach to be very representative when used previously. This enables the gas substitution ratio (GSR) to be calculated in terms of how much of the carbon leaving the tailpipe originated from methane, and by subtraction the remainder originating from diesel.

In addition, both vehicles were tested on the track, during which the PEMS equipment analysed the tailpipe emissions. Whilst this is sometimes referred to as “on-the-road driving” because it was on a test track, neither road markings, nor other traffic determined the speed-road cycle used. Therefore, the vehicle was driven over the same speed-time profile as was used on the chassis dynamometer, and PEMS data was collected. This enables the direct comparison with the PEMS data collected during the chassis dynamometer testing, and allows comparison of on-road and chassis dyno testing. The on-road testing was replicated three times. Prior to the start of this project, an order had been placed for a PEMS methane monitoring analyser. However, at the time of testing this equipment had not arrived, and direct measurement of methane by PEMS was not possible. For the reasons outlined already in this report, however, indirect measurement of methane by using THC as a proxy is acceptable.

For the dedicated methane truck, where the catalyst is an integral part of the OEM build, this testing was with the catalyst present. However, for the dual fuel after-market converted tractor unit, track testing was undertaken with and without the catalyst present. Further details are given in subsequent sections where the details of the testing is described more fully, and the results are presented.

4.1.3 Drive cycle used

Section 3.1 describes the range of drive cycles potentially available, and Section 3.6 concludes that, from the desk based study, the drive cycle to be used in the vehicle testing is the World Harmonised Vehicle Cycle (WHVC). This is shown in Figure 4-2 and is reproduced here, to accompany the analysis below.

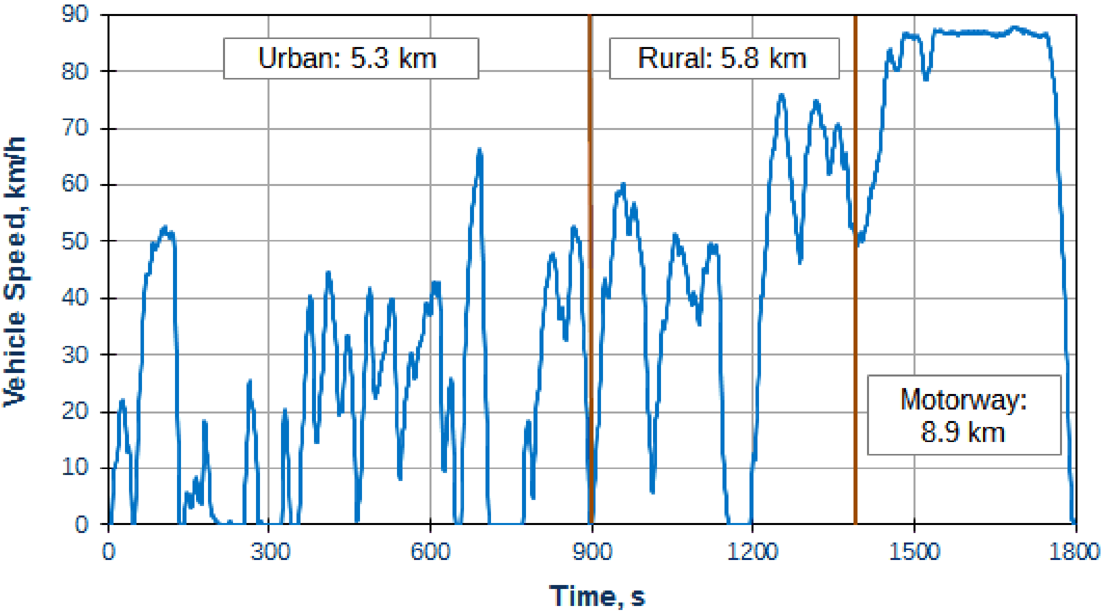
An analysis of the WHVC time-speed profile generates the following characteristic for the three phases and the whole cycle.

Table 4-2: Characteristic for the three phases that comprise the WHVC

Segment	Duration (s)	Distance (km)	Average speed (km/hr)	Kinetic Intensity[49] (1/km)
Phase 1	900	5.32	21.28	4.458
Phase 2	442	5.12	41.70	1.135
Phase 3	458	9.63	75.70	0.113
Combined	1800	20.07	40.14	1.030

Many of the results presented give average emissions expressed in g/km for these three phases and the whole cycle.

Figure 4-2 - World Harmonised Vehicle Cycle (WHVC)



Source: Dieselnet, 2013

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[49] Kinetic intensity, KI, is a metric linked to the magnitude and frequency of accelerations. The bigger the magnitude and frequency of accelerations, the larger the value of the Kinetic Intensity. The unit of Kinetic Intensity is reciprocal distance. It is calculated by taking the ratio of characteristic acceleration to the square of aerodynamic speed

4.1.4 Comparator vehicles

To allow a more complete understanding of the difference in emissions that result from using a dual-fuel gas vehicle compared with a conventional pure diesel vehicle, some data was collected from the dual-fuel vehicle in its “diesel–only” mode on the chassis dynamometer. This both provided a calibration of the diesel fuel flow meter (relating its output to the tailpipe carbon emissions) and gave emissions data for the operation of the dual fuel vehicle in “diesel–only” mode.

The option of running the same vehicle using diesel only, and then in its methane consuming mode does not apply to the dedicated gas vehicle which cannot run on diesel fuel. Therefore for this vehicle two comparisons were undertaken:

- Using data from an earlier study (Cenex Coca-Cola Enterprises) where a diesel comparator vehicle was tested alongside the dedicated methane vehicle; and
- Using standard CO_2 emission factors from the COPERT 4 v10 model.

4.2 Results from testing dedicated methane vehicle

4.2.1 Overview of testing of dedicated methane vehicle

An overview of the general test arrangement in terms of the analysers, the test bench and the driving cycle are given in Section 4.1. These were followed during the testing of the Iveco dedicated methane vehicle.

In terms of the actual tests, and the test conditions the truck was tested on four replicates of the WHVC in the VTEC facility, i.e. using a chassis dynamometer, and three times on the track, again driving the WHVC. These tests are summarised in Table 4-3.

The dynamometer settings used for the chassis dynamometer were estimates derived from over a decades vehicle testing. In essence Millbrook have developed a series of “cook book equivalent” road load parameters that are referred to when coast down data is not available.

Table 4-3: Summary of testing undertaken with dedicated methane vehicle

Test number	Cycle	Date
ML02014412	WHVC hot start	2/2/2015
ML02014413	WHVC hot start	2/2/2015
ML02014415	WHVC hot start	2/2/2015
ML02014416	WHVC hot start	2/2/2015
Iveco Track Run 1	WHVC hot start	4/2/2015
Iveco Track Run 2	WHVC hot start	4/2/2015
Iveco Track Run 3	WHVC hot start	4/2/2015

The remainder of this section reports the analysis of the data collected in terms of the key questions identified in the previous section, namely:

- What level of methane slip occurred?
- How does the level of methane slip vary with key test and vehicle parameters (e.g. speed, loading)?
- What is the difference between measuring THC and methane?
- What is the impact of the catalyst?

The question regarding the consequences of the data collected on the design and robustness of the proposed test protocol is covered later, when the data from both the dedicated methane and dual fuel vehicles are considered together.

4.2.2 The overall tailpipe methane slip, CO_2 and NOx emissions over the WHVC

From Figure 4-1 there are four different measurements of the tailpipe emissions:

1. The regulatory bag emissions measurement;
2. Tailpipe emissions from aggregation of modal data;
3. Tailpipe emissions for a sub-set of species from aggregation of FTIR data; and
4. Tailpipe emissions from aggregation of PEMS data.

Data was obtained for each of the three phases of the WHVC, and for the combined cycle. The data from the four runs for the four different measurements are in Table 4-4 for HC, CO_2 and NOx.

Table 4-4: Summary of total hydrocarbons emitted from chassis dynamometer testing of the dedicated methane vehicle

Data Source	Bag		Tailpipe modal		FTIR tailpipe		PEMS tailpipe	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)
Phase 1 Urban	0.219	3.9%	0.286	8.1%	0.183	37.4%	0.444	21.0%
Phase 2 Rural	0.260	12.9%	0.252	12.0%	0.161	13.2%	0.356	22.6%
Phase 3 Motorway	0.801	7.8%	0.705	8.2%	0.384	16.8%	0.925	14.4%
Combined result	0.490	7.6%	0.463	8.8%	0.266	17.9%	0.632	16.5%

For total hydrocarbons, the emissions are small, around 0.5g/km over the combined cycle. It is noted that:

- There is good agreement between the standard bag and modal tailpipe data.
- The standard deviation for the four runs is typically around 10% of these measurements, although it spans 4%-13%;
- The FTIR data, which is for methane only, is systematically low, being around 55% of the bag and modal data, and a higher standard deviation; and
- The data from the PEMS system is systematically **high**, being around 133% of the bag and modal data.

For a Euro V gas fuelled engine the permissible emissions over the ETC (engine cycle) are 1.1 g/kWh for methane and 0.56 g/kWh for NMHC. This is a total of 1.66 g/kWh for all hydrocarbons.

The energy absorbed by the dynamometer can be calculated, and is around 0.65kWh per km travelled. When transmission losses from the engine to the dynamometer are included, such as the automatic gearbox, tyres etc., it is likely that this is around 1 kWh/km power delivered by the engine. This also correlates with the CO_2 emissions.

Therefore, if the assumption is made that the vehicle's engine generates 1 kWh/km for this test cycle, then the THC emissions are around 30% of the regulatory standard.

The equivalent data for CO_2 and NOx emissions are tabulated below.

Table 4-5: Summary of CO_2 emissions from chassis dynamometer testing of the dedicated methane vehicle

Data Source	Bag		Tailpipe modal		FTIR tailpipe		PEMS tailpipe	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Measure	Mean (g/km)	Stdev (%)	Mean (g/km)
Phase 1 Urban	1,214.1	2.5%	1,199.2	0.9%	1,272.7	4.8%	1,449.2	2.1%
Phase 2 Rural	855.0	1.2%	853.1	0.9%	894.3	6.4%	991.0	2.2%
Phase 3 Motorway	757.6	1.0%	767.8	1.0%	807.9	2.4%	871.8	1.7%
Combined result	907.0	1.5%	907.1	0.8%	956.3	3.8%	1,059.7	1.8%

Table 4-6: Summary of NOx emissions from chassis dynamometer testing of the dedicated methane vehicle

Data Source	Bag		Tailpipe modal		FTIR tailpipe		PEMS tailpipe	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Measure	Mean (g/km)	Stdev (%)	Mean (g/km)
Phase 1 Urban	1.938	11.8%	2.038	20.2%	1.893	3.2%	2.720	9.1%
Phase 2 Rural	0.631	11.4%	0.660	35.6%	0.629	18.3%	0.858	9.0%
Phase 3 Motorway	0.090	17.0%	0.096	7.4%	0.117	11.6%	0.142	8.6%
Combined result	0.737	10.2%	0.775	22.8%	0.736	5.4%	1.034	8.0%

For these data it is noted:

- There is good agreement between the standard bag, modal tailpipe and FTIR data;
- The standard deviation for the four runs is typically around 1% for CO_2, although when the first phase of the first run is included, which is around 5% higher than the others this rises to 2%. For NOx and around 14% for NOx; and
- The data from the PEMS system is systematically **high**, being around 117% of the other measurements for CO_2 and 137% of the other measurements for NOx.

Again it is noted that the overall NOx emissions levels (around 0.75 g/km) are well below the Euro V emission standard of 2.0 g/kWh, assuming that this vehicle's engine is around 1 kWh/km power.

4.2.3 The difference between measuring THC and methane

Methane measurements are provided by the FTIR instrument only. The comparison is of the FTIR data and the total hydrocarbon (THC) FID data (or comparable bag data for THC). The first analysis is to assess whether the FTIR, modal and bag data are directly comparable. The CO_2 and NOx measurements of Tables 4-5 and 4-6 indicate that for these emissions the FTIR results are comparable with the bag and aggregated modal data, and that the FTIR measurements are not systematically different from other measurements.

Comparison of the FTIR methane measurement and THC (FID) measurement indicates that not all the THC is methane. This is as anticipated. The data indicates that the NMHC component of the THC is around 0.2 g/km for the combined cycle, is less than 0.1 g/km for Phases 1 and 2 of the cycle, but is around 0.37 g/km for Phase 3. Even for this relatively high proportion of NMHC, the non-methane component is <50% of the THC.

4.2.4 The impact of the catalyst

Table 4-7 gives the pre and post catalyst data for CO_2, CO, THC and NOx. The first two columns are from the aggregated modal data, whilst the third column is the tailpipe bag measurements. The final three columns show the impact of the catalyst.

The changes caused by the catalyst are calculated by considering the pre- and post-catalyst emissions on a run by run basis, calculating the change caused by the catalyst for each run, and then taking the average of these.

For HC the overall reduction in emissions due to the catalyst is 96.4%, for CO it is 90.0% and for NOx it is 95.5%. The CO_2 concentration increases, because of the oxidation of hydrocarbons and CO to CO_2. It is interesting to note that around 11% of the tailpipe CO_2 is formed by oxidation after the engine.

The data for the combined cycle actually contains some other interesting trends. For Phase 1 of the cycle the reductions in THC and CO concentrations are 98.1 and 93.9%, whereas for Phase 3 they are 93.2% and 85.8%. The amount of oxidation occurring is therefore less for the higher speed phase. In contrast the reduction in NOx emissions increases from 90.0% for Phase 1 to 95.5% for the higher speed phase. This is all consistent with the exhaust stream being less oxidising at higher speeds/engine powers.

Overall, these data clearly show the catalyst is making a large impact, acting effectively in both oxidising and reducing mode.

Table 4-7: Emissions results showing the impact of the catalyst (dedicated methane vehicle)

	Pre-catalyst Mean (g/km)	**Post catalyst** Mean (g/km)	**Bag (post catalyst)** Mean (g/km)	**Change caused by Catalyst** (%)
		CO_2		
Phase 1 Urban	1067.0	1199.2	1214.1	+12.2%
Phase 2 Rural	757.2	853.1	855.0	+12.7%
Phase 3 Motorway	705.9	767.8	757.6	+8.8%
Combined result	817.2	907.1	907.0	+11.0%
		CO		
Phase 1 Urban	58.309	3.597	2.078	-93.9%
Phase 2 Rural	38.435	4.531	3.823	-88.4%
Phase 3 Motorway	23.129	3.283	3.230	-85.8%
Combined result	36.902	3.726	3.095	-90.0%
		THC		
Phase 1 Urban	15.508	0.286	0.219	-98.1%
Phase 2 Rural	14.198	0.252	0.260	-98.2%
Phase 3 Motorway	10.635	0.705	0.801	-93.2%
Combined result	12.961	0.463	0.490	-96.4%
		NOx		
Phase 1 Urban	20.177	2.038	1.938	-90.0%
Phase 2 Rural	15.118	0.660	0.631	-95.7%
Phase 3 Motorway	16.372	0.096	0.090	-99.4%
Combined result	17.018	0.775	0.737	-95.5%

4.2.5 Emissions as a function of speed

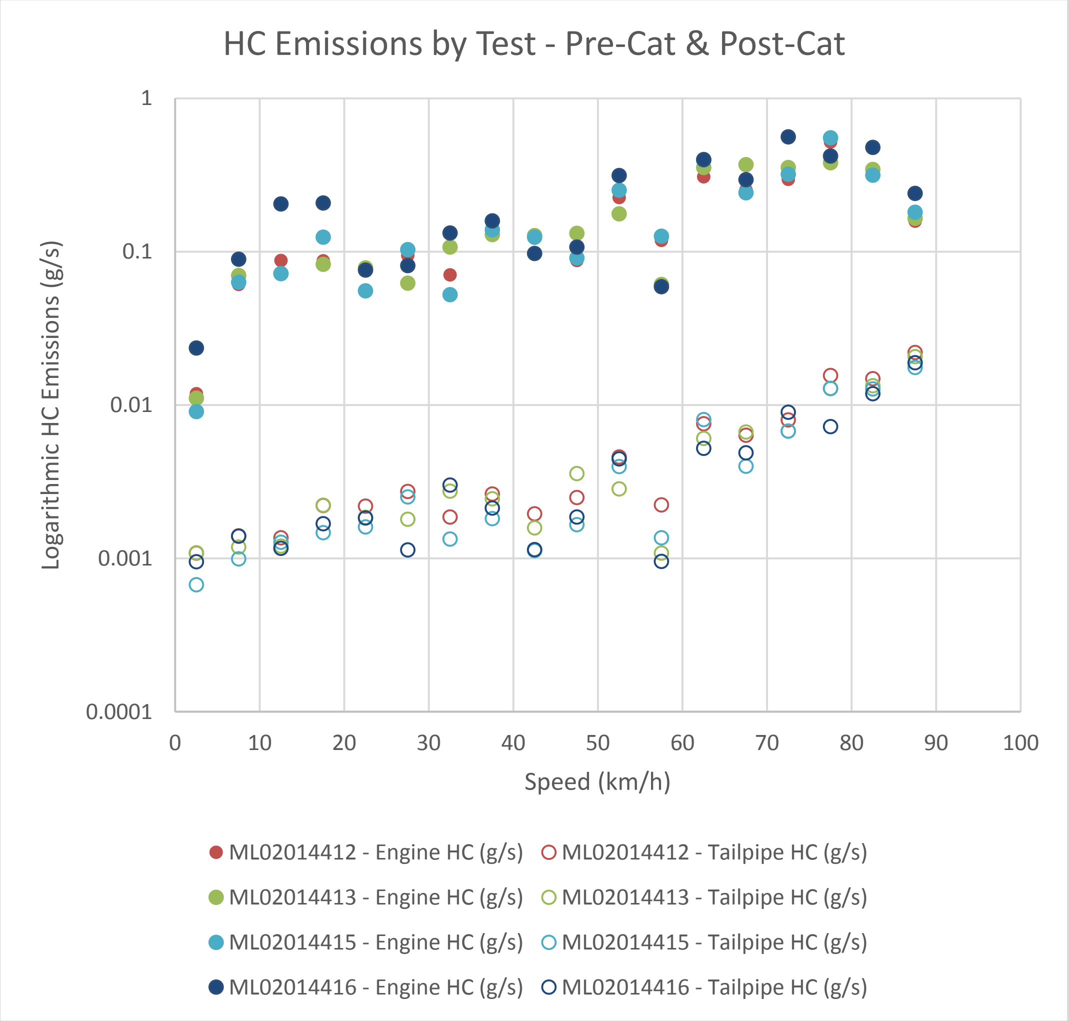
An important aspect of the protocol is that it will involve collecting methane slip (or THC emissions) over the whole range of speeds from stationary to 90 km/h. It is recommended these are weighted by the ratios given in Regulation 582/2011/EC, namely 20% for the speed range 0 – 50 km/h, 25% for the speed range 50 – 75 km/h, and 55% for the speed range above 75 km/h. An understanding as to how the methane slip varies with speed provides an indication as to how sensitive the overall assessment of methane slip is to these ratios.

Whilst answers may be presented using the metric of g/km, the direct measurement is of the instantaneous rate of methane emissions, i.e. g/second. Plotting this instantaneous rate of methane emissions against speed is very noisy, and it is difficult to discern patterns. Therefore the modal pre- and post-catalyst FID data was analysed using the steps described below:

- The 1800 seconds of each of the WHVC chassis dynamometer tests was split into 180 consecutive 10 second segments.
- For each of the ten second segments the average HC emissions, and the average speed was calculated.
- Data were then aggregated further by combining all ten second segments within 5 km/h average speed windows, i.e. for 0 – 4.999 km/h, 5.0 – 9.999 km/h, 10.0 – 14.999 km/h etc, and averaging these.

This gives the average emissions for 10 second segments, by speed, for each of the four chassis dynamometer tests, for both pre- and post-catalyst THC. This is plotted in Figure 4-3:

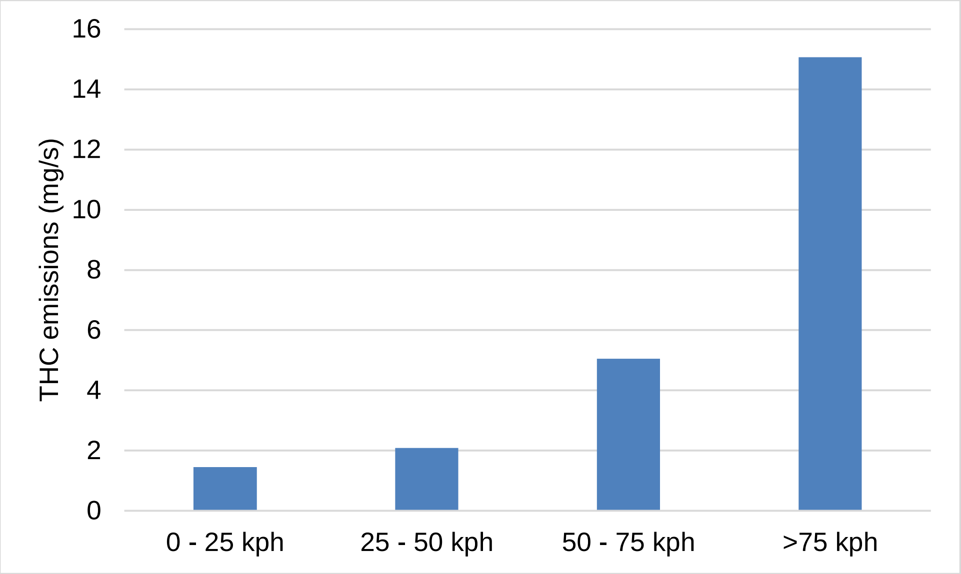
Figure 4-3 – Pre- and post-catalyst THC emissions over the WHVC as a function of speed (dedicated methane vehicle)



Even at this high level of aggregation the data are somewhat noisy, although the peaks and troughs are not thought to be significant. Note the graph is plotted on a logarithmic vertical axis, so the range is around a factor of 20. This is shown on a linear vertical scale for four speed ranges, in Figure 4-4[50].

This graph clearly shows how the THC (methane slip) emissions are markedly larger at higher speeds. But it is emphasised that overall these are low emissions.

Figure 4-4 – Post-catalyst THC emissions over the WHVC for different speed ranges (dedicated methane vehicle)



4.2.6 Emissions during on the road (track) driving

In addition to the four WHVCs run on the chassis dynamometer, a further three WHVCs were run on a test track, as summarised in Table 4-3.

Table 4-8 summarises the data collected using PEMS only for these two groups of emissions tests.

The data in the table indicates:

- For CO_2, which is closely related to the amount of energy generated by the vehicle, there is a systematic difference which is significantly larger than the uncertainty in the measurements.
- The decrease in CO_2 emissions for the track testing is systematically related to the average speed of the cycle. This indicates the retarding forces applied on the dynamometer are increasingly too high at higher speed, i.e. the windage retarding force, F2, is too large. This leads to the reductions following the order: Motorway > Rural > Urban.
- Along with the reduction in CO_2 emissions there is a reduction in hydrocarbon emissions.
- However, the reduction in HC emissions is not linear with increasing speed, but is in the order Motorway > Urban > Rural. This is relatively large for the motorway cycle (around a factor of 5) however, in absolute terms the difference is small (all emissions < 1 g/km) and leads to little impact in the change in GHG emissions. The origin of this difference is probably a combination of the measurement accuracy (a random effect) and the change in applied load (a systematic effect discussed above).
- There is also a reduction in NOx emissions, but for these the order of the reductions is the opposite of that for CO_2, namely Urban > Rural > Motorway. However, the order of the size of the emissions is also Urban > Rural > Motorway.
- It has also been established, from other independent tests, that the PEMS flow tube calibration when within the CVS can go outside its linear range, and develop an offset. This additional

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[50] (now to right of figure above in the spreadsheet)

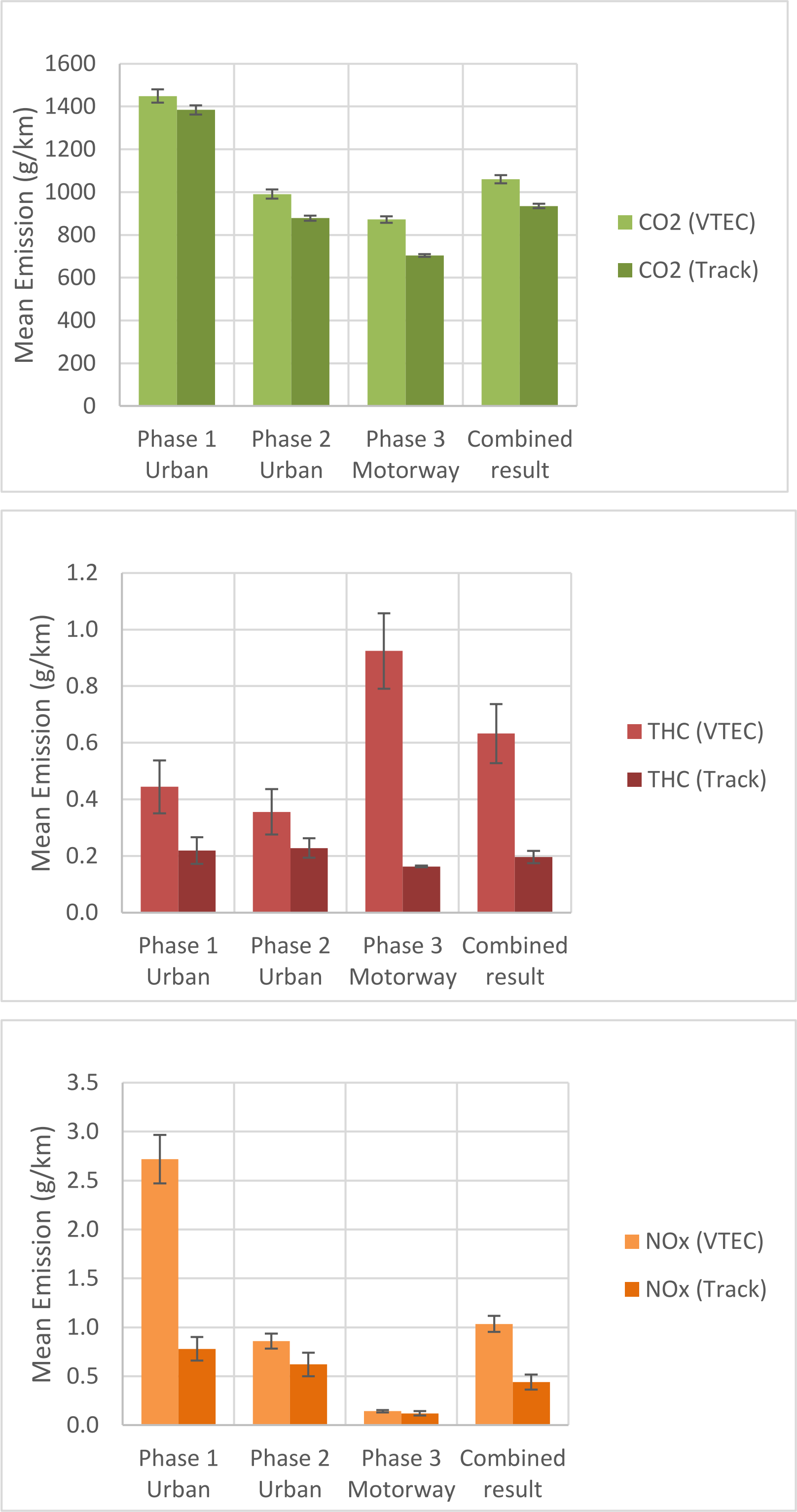
complication also leads to systematic differences between the VTEC and Track emissions for the same driving cycle.

- The overall message from the data in Table 4-8 is that it is difficult to predict changes in HC or NOx emissions even when the change in CO_2 emissions is known. The corollary to this is the value of developing a measurement protocol, rather than inferring, for example, changes in HC emissions from known change in CO_2 emissions. The data in Table 4-8 is shown in Figure 4-5.

Table 4-8: PEMS Emissions results for chassis dynamometer and track testing (dedicated methane vehicle)

Measure	PEMS VTEC tests		PEMS Track tests		Ratio track to VTEC
	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	
THC					
Phase 1 Urban	0.444	21.0%	0.219	21.3%	49%
Phase 2 Rural	0.356	22.6%	0.228	15.1%	64%
Phase 3 Motorway	0.925	14.4%	0.163	1.9%	18%
Combined result	0.632	16.5%	0.197	11.1%	31%
CO_2					
Phase 1 Urban	1449.2	2.1%	1384.2	1.6%	96%
Phase 2 Rural	991.0	2.2%	878.2	1.4%	89%
Phase 3 Motorway	871.8	1.7%	703.5	0.9%	81%
Combined result	1059.7	1.8%	935.2	1.2%	88%
NOx					
Phase 1 Urban	2.720	9.1%	0.780	15.4%	29%
Phase 2 Rural	0.858	9.0%	0.620	19.6%	72%
Phase 3 Motorway	0.142	8.6%	0.121	18.2%	85%
Combined result	1.034	8.0%	0.441	17.1%	43%

Figure 4-5 – Comparison of CO_2, HC and NOx emissions for chassis dynamometer and track testing of dedicated methane vehicle over the WHVC [51]



The systematic change in CO_2 emissions for the track testing relative to dynamometer testing, with the average speed of the cycle is shown in Table 4-6. The three blue points represent the ratios for the three phases of the WHVC and the green point represents the combined cycle.

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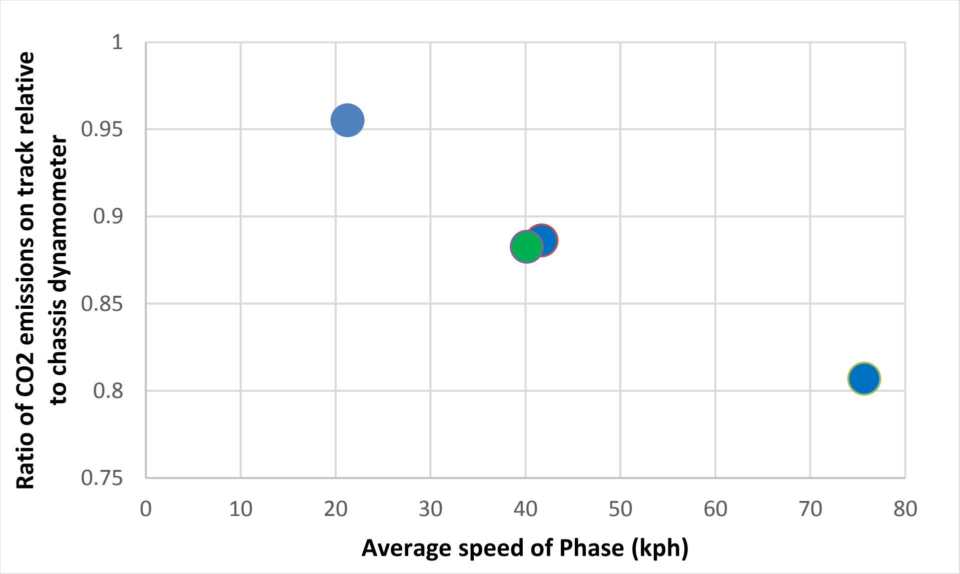
[51] Tab – Report tables (row 47-); Workbook – Iveco Analysis v1.5 xlsx

Figure 4-6 – Ratio of CO_2 emissions from track and dynamometer testing of dedicated methane vehicle for the different phases of the WHVC[52]



4.2.7 PM emissions

No second by second measurement of PM was possible using the standard analysis suite, nor was PM measurement part of PEMS capability for the system used. Therefore only single data points are available (albeit disaggregated by drive cycle Phase) for each VTEC test, and there is no track test data.

The analysis of the cycle phase data gave the results obtained in Table 4-9. The results are inconsistent with the overall emissions for diesel vehicles, and the dual fuel vehicle, see Section 4.3.8. In the context of other emissions data from dedicated methane vehicles, the values obtained are believed to be unreasonably high, and generally thought to be unreliable. The overall conclusion is that no useful PM measurements were obtained during these studies.

Table 4-9 – Bag PM Data by cycle

Data Source	Bag	
Measure	Mean (g/km)	Stdev (%)
Phase 1 Urban	0.199	21.2%
Phase 2 Rural	0.151	18.7%
Phase 3 Motorway	0.724	20.7%
Combined result	0.419	19.8%

4.2.8 Overall GHG emissions

The CO_2 and methane emissions (using THC measurements as a proxy for methane) can be combined to give overall GHG emissions. These are shown in Figure 4-7 for the three components of the WHVC and the combined cycle. From this figure it can be seen that the relative contribution of the methane emissions is small, despite its GWP of 28; it is larger for the motorway phase of the cycle for the chassis dynamometer testing, and in the combined cycle and is just evident for the urban and rural cycles.

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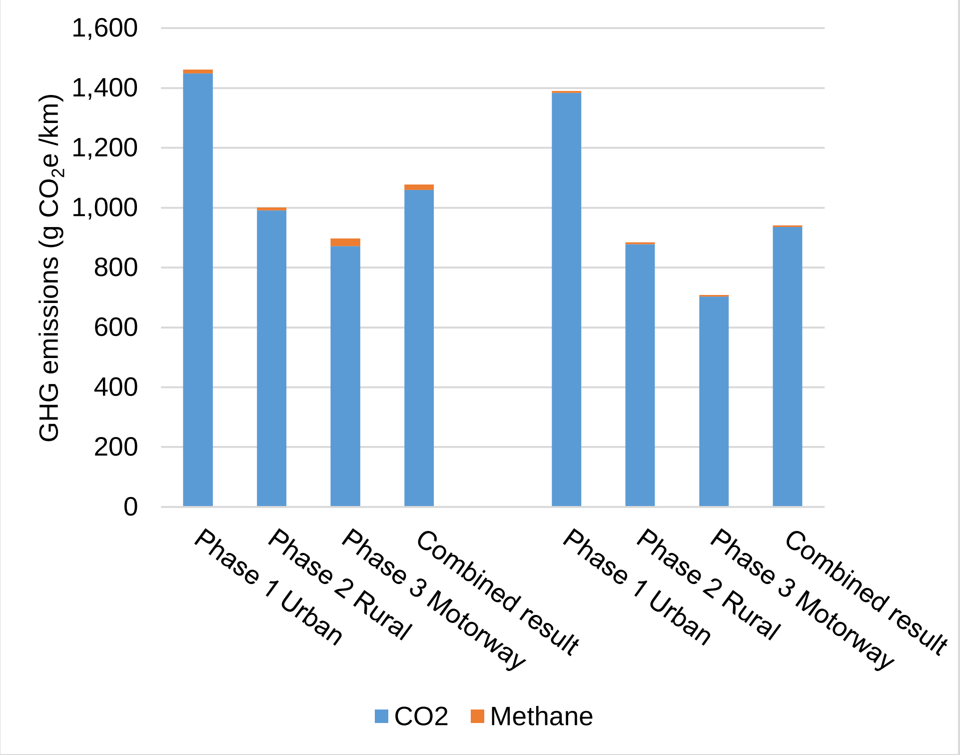
[52] Tab – Stream analysis; Workbook – Iveco Analysis v3.0 xlsx

Figure 4-7 – The greenhouse gas emissions from the dedicated methane fuelled vehicle for dynamometer and track testing over the three phases of the WHVC



This dedicated methane fuelled vehicle could not be run on diesel fuel to provide a diesel only comparator directly. However, an indication of the overall change in GHG emissions can be obtained from standard emission factors, and from the Coca Cola research project cited earlier in this report and below.

The standard CO_2 emissions for a 20 – 26 (and 26 – 28) tonne Euro V rigid truck, with 50% loading on a flat road are 798 (and 850) g CO_2/km from the emissions factors given in the EMEP/EEA Emission Inventory Guidebook for 2013[53] at 40 kph (the average speed over the combined WHVC).

In 2012 Coca-Cola Enterprises undertook a biomethane trial, managed by Cenex, which compared the emissions of a dedicated methane truck with a diesel comparator[54]. On page 14 of the Coca Cola report the raw data provided shows that the gas truck used on average 34.9 kg fuel per 100 km, whilst the diesel truck used 31.9 litres diesel per 100 km. When converted into CO_2 emissions these approximate to the gas truck emitting 960g CO_2/km and the diesel truck emitting 851g CO_2/km. Therefore from the CCE study, the CO_2 emissions of the gas truck were 112.8% of those from the diesel comparator.

The figure reported in the CCE trial for the methane fuelled vehicle, 960g CO_2/km, is very similar to the 935g CO_2/km for the combined WHVC track testing found in this study. Also the CO_2 emissions factors given in the EMEP/EEA Emission Inventory Guidebook of around 850g/km is very close to that found in the CCE trial.

From this study the CO_2 emissions over the combined WHVC was 935.2g CO_2/km, which when the methane emissions are included increased to give CO_2e emissions of 940.7g CO_2e/km.

These data indicate that for the vehicle tested general reductions in overall engine efficiency cause the methane truck to have higher GHG emissions than its diesel comparator from CO_2 emissions alone. However, this study indicates methane slip contributes a little less than 0.6% of the around 12% overall increase.

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[53] Available from http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

[54] Report on the Coca-Cola Enterprises Biomethane Trial Report available from http://www.cenex.co.uk/wp-content/uploads/2014/02/CCE-biomethane-trial-report-1_3.pdf

4.3 Results from testing dual fuel diesel/methane vehicle

4.3.1 Overview of dual fuel truck testing

An overview of the general test arrangement in terms of the analysers, the test bench and the driving cycle is given in Section 4.1. These arrangements were followed during the testing of the dual fuel methane/diesel truck.

Relative to the dedicated methane fuelled truck, testing a dual fuel truck has both an additional dimension, and an additional parameter to be considered. These are data from the same vehicle in diesel only mode, and, when operating in dual fuel mode, there is the gas substitution ratio (GSR).

The truck was tested with a single run in diesel only mode, and then five replicates of the WHVC (hot start) in the VTEC facility, i.e. using a chassis dynamometer. For three of these the FTIR analyser sampled the tailpipe gas stream, whilst for the last two replicated, the FTIR analyser sampled the engine out gas stream. On the track, again driving the WHVC, the truck was tested three times with the catalyst present, and for three runs when the catalyst had been replaced by the original section of exhaust with no catalyst present. These are summarised in Table 4-10.

Table 4-10: Summary of testing undertaken with the dual fuel vehicle

Test number	Weight and FTIR analysis point	Fuel	Date	Comments
ML02014388	20 tonnes, exhaust	Diesel only	6/1/2015	Catalyst present
ML02014389	20 tonnes, exhaust	Methane/diesel DF	6/1/2015	Catalyst present
ML02014391	20 tonnes, exhaust	Methane/diesel DF	6/1/2015	Catalyst present
ML02014392	20 tonnes, exhaust	Methane/diesel DF	6/1/2015	Catalyst present
ML02014393	20 tonnes, engine	Methane/diesel DF	6/1/2015	Catalyst present
ML02014394	20 tonnes, engine	Methane/diesel DF	7/1/2015	Catalyst present
DF Track Run 1	30 tonnes N/C	Methane/diesel DF	14/1/2015	Catalyst present
DF Track Run 2	30 tonnes N/C	Methane/diesel DF	14/1/2015	Catalyst present
DF Track Run 3	30 tonnes N/C	Methane/diesel DF	14/1/2015	Catalyst present
DF Track Run 4	30 tonnes N/C	Methane/diesel DF	17/1/2015	No catalyst
DF Track Run 5	30 tonnes N/C	Methane/diesel DF	17/1/2015	No catalyst
DF Track Run 6	30 tonnes N/C	Methane/diesel DF	17/1/2015	No catalyst

As for the dedicated methane truck, the settings used for the chassis dynamometer were estimates derived from over a decade of vehicle testing. In essence Millbrook have developed a series of “cook book equivalent” road load parameters that are referred to when coast down data is not available. The dynamometer’s settings for vehicle inertia and road load were those simulating a 20 tonne tractor-trailer combination, whilst for the track testing the curtain trailer was loaded to give a 30 tonne combined vehicle weight. The former was limited by the chassis dynamometer’s capacity.

4.3.2 The overall tailpipe methane slip, CO_2 and NOx emissions over the WHVC

From Figure 4-1 there are four perspectives of the tailpipe emissions:

1. The regulatory bag emissions measurement;
2. Tailpipe emissions from aggregation of modal data;

3. Tailpipe emissions for sub-set of species from aggregation of FTIR data; and
4. Tailpipe emissions from aggregation of PEMS data.

Data was obtained for each of the three phases of the WHVC, and for the combined cycle. The data from the single diesel only run, and the average of the five dual fuel runs for the four different measurements are summarised below for HC, CO_2, NOx and CO.

Table 4-11: Summary of total hydrocarbons emitted from chassis dynamometer testing of the dual fuel vehicle

Data Source	**Bag**		**Tailpipe modal**		**FTIR tailpipe**[55]		**PEMS tailpipe**	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)
Diesel only mode								
Phase 1 Urban	N/A	Note 1	0.236		0.021		0.028	
Phase 2 Rural	N/A		0.097		0.004		0.002	
Phase 3 Motorway	N/A		0.045		0.000		0.002	
Combined result	N/A		0.111		0.006		0.009	
Dual fuel mode								
Phase 1 Urban	14.295	34.0%	14.710	32.6%	18.187	2.8%	20.789	1.6%
Phase 2 Rural	10.961	10.0%	11.026	9.8%	13.659	1.0%	14.772	3.1%
Phase 3 Motorway	16.690	6.2%	16.658	6.1%	24.194	3.0%	29.133	1.7%
Combined result	14.403	14.2%	14.515	13.9%	19.946	2.3%	22.791	1.7%

Note 1: For the single diesel only run no standard deviation exists.

Some comments on these data are as follows:

- When operating in the diesel only mode there are very low HC emissions;
- In dual fuel mode there are much higher HC emissions;
- In dual fuel mode the bag and modal results are very similar;
- But for the FTIR analysis of methane (CH_4) only, this result is higher – but not by a constant amount. It varies from being around 25% too high for Phases 1 and 2 to being 45% too high for Phase 3, with the combined cycle being 38% too high; and
- The PEMS data is higher still, being around 55% higher than the mean of the bag and tailpipe modal data.

The reason for high values is not known and further analysis of this issue is outside the scope of this project.

The equivalent data for CO_2, NOx and PM emissions are given in the three following tables.

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[55] These data are from averaging runs ML02014389, ML02014391 and ML02014392 only, when the FTIR instrument analysed the exhaust gas stream

Table 4-12: Summary of CO_2 emissions from chassis dynamometer testing of the dual fuel vehicle

Data Source	Bag		Tailpipe modal		FTIR tailpipe[56]		PEMS tailpipe	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)
Diesel only mode								
Phase 1 Urban	1132.2	Note 1	1127.3		1187.8		1332.3	
Phase 2 Rural	790.4		771.6		848.3		929.4	
Phase 3 Motorway	670.7		668.1		664.4		815.3	
Combined result	828.7		820.8		851.1		986.5	
Dual fuel mode								
Phase 1 Urban	1095.9	0.5%	1100.0	0.6%	1135.1	0.7%	1281.4	1.8%
Phase 2 Rural	759.4	0.3%	750.7	0.4%	808.8	0.3%	877.0	1.3%
Phase 3 Motorway	613.8	0.7%	616.5	0.7%	599.7	0.6%	728.9	2.3%
Combined result	781.9	0.3%	781.6	0.4%	792.6	0.3%	916.0	1.8%

Note 1: For the single diesel only run no standard deviation exists.

Table 4-13: Summary of NOx emissions from chassis dynamometer testing of the dual fuel vehicle

Data Source	Bag		Tailpipe modal		FTIR tailpipe[57]		PEMS tailpipe	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)
Diesel only mode								
Phase 1 Urban	9.958	Note 1	10.205		10.314		12.575	
Phase 2 Rural	4.453		4.424		4.431		5.541	
Phase 3 Motorway	3.458		3.514		3.410		4.521	
Combined result	5.483		5.565		5.549		6.968	
Dual fuel mode								
Phase 1 Urban	2.582	18.6%	2.282	18.6%	2.756	15.8%	3.182	19.3%
Phase 2 Rural	2.294	5.0%	2.038	4.5%	2.292	6.9%	2.824	4.5%
Phase 3 Motorway	0.653	8.2%	0.622	7.2%	0.624	12.5%	0.878	5.8%
Combined result	1.632	9.1%	1.466	8.5%	1.605	11.3%	2.044	9.4%

Note 1: For the single diesel only run no standard deviation exists.

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[56] These data are from averaging runs ML02014389, ML02014391 and ML02014392 only, when the FTIR instrument analysed the exhaust gas stream

[57] These data are from averaging runs ML02014389, ML02014391 and ML02014392 only, when the FTIR instrument analysed the exhaust gas stream

Table 4-14: Summary of CO emissions from chassis dynamometer testing of the dual fuel vehicle

Data Source	Bag		Tailpipe modal		FTIR tailpipe[58]		PEMS tailpipe	
Measure	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)
Diesel only mode								
Phase 1 Urban	0.200	Note 1	0.155		0.074		0.842	
Phase 2 Rural	0.012		0.021		0.001		0.344	
Phase 3 Motorway	0.005		0.014		0.001		0.237	
Combined result	0.059		0.054		0.077		0.429	
Dual fuel mode								
Phase 1 Urban	0.529	137.7%	0.587	126.2%	0.014	29.4%	1.507	92.7%
Phase 2 Rural	0.015	39.3%	0.030	43.4%	0.001	43.1%	0.672	44.1%
Phase 3 Motorway	0.005	14.1%	0.020	34.0%	0.000	7.9%	0.616	40.1%
Combined result	0.145	130.1%	0.171	109.8%	0.004	28.5%	0.865	60.8%

Note 1: For the single diesel only run no standard deviation exists.

Table 4-15: Summary of PM emissions phases of whole cycle only from chassis dynamometer testing of the dual fuel vehicle

Data Source	Bag	
Measure	Mean (g/km)	Stdev (%)
Diesel only mode		
Phase 1 Urban	0.200	Note 1
Phase 2 Rural	0.012	
Phase 3 Motorway	0.005	
Combined result	0.059	
Dual fuel mode		
Phase 1 Urban	0.529	137.7%
Phase 2 Rural	0.015	39.3%
Phase 3 Motorway	0.005	14.1%
Combined result	0.145	130.1%

Note 1: For the single diesel only run no standard deviation exists.

For these data it is noted that in dual fuel mode, relative to the diesel only mode:

- NOx emissions are reduced overall by around 70%, to around 30% of the diesel only value;
- The extent of the reduction varies being around 50% for Phase 2 but greater than 80% for Phase 3;
- The reductions are virtually the same for all four analysis techniques;
- CO emissions at the tailpipe remain low, and are therefore somewhat variable, but are above the diesel only value by, on average, around a factor of two for the modal, bag and PEMS data;
- CO emissions appear to be reduced from FTIR measurement (probably due to interference, making this measurement unreliable);
- CO_2 emissions at the tailpipe are reduced by around 3.5% for Phases 1 and 2, and by around 8.5% for Phase 3.
- The changes are virtually the same for all four analysis techniques.

---

[58] These data are from averaging runs ML02014389, ML02014391 and ML02014392 only, when the FTIR instrument analysed the exhaust gas stream

The two important messages from the above list are:

- In dual fuel mode, NOx emissions are significantly reduced when the vehicle operates in dual fuel mode; and
- Although the PEMS emission rates are different from those measured by other techniques, when comparing the diesel only relative to the dual fuel mode, the changes measured by PEMS are directly comparable with those measured by the other analysis methods.

4.3.3 The difference between measuring THC and methane

Methane measurements are provided by the FTIR instrument only. The comparison is of the FTIR data and the total hydrocarbons (THC) FID data (or comparable bag data for THC).

It was noted earlier that when driving in dual fuel mode the bag and modal results are very similar. However, the FTIR methane measurement is higher than the bag and modal THC results – but not by a constant amount. It varies from being around 25% higher for Phases 1 and 2 to being 45% higher for Phase 3, with the combined cycle being 38% higher. For this analysis the data are not unequivocal, but there are no data that suggest anything other than the vast majority of the increased hydrocarbon emissions are other than of methane.

The principal purpose of having the FTIR present is to indicate how much hydrocarbon (HC), as indicated by FID detectors, is methane. The very low HC for the modal data when in diesel fuel only mode, and combined with the currently inexplicably high FTIR result for methane when in dual fuel mode, both support the view that the vast majority >95% (possibly >99% for these data) of the tailpipe HC in dual fuel mode is methane.

These data strongly support the view that a THC (FID) rather than methane specific HC analyser is appropriate for this methane slip measurement protocol.

4.3.4 The impact of the catalyst

Table 4-16 gives the pre and post catalyst data for CO_2, CO, THC and NOx when the vehicle was tested in dual fuel mode on the chassis dynamometer.

Table 4-16: Pre and post-catalyst data from the VTEC testing in dual fuel mode

	Modal pre-catalyst	Modal post-catalyst	Catalyst impact	FTIR pre-catalyst	FTIR post-catalyst	Catalyst impact	Bag (post catalyst)
	Mean (g/km)	Mean (g/km)	(%)	Mean (g/km)	Mean (g/km)	(%)	Mean (g/km)
CO_2							
Phase 1 Urban	1054.2	1100.0	+3.8%	1328.6	1135.1	85.4%	1096.0
Phase 2 Rural	724.3	750.7	+3.2%	916.1	808.8	88.3%	759.4
Phase 3 M'way	578.9	616.5	+5.5%	604.7	599.7	99.2%	613.8
Combined result	745.1	781.6	+4.2%	872.9	792.6	90.8%	781.9
CO							
Phase 1 Urban	20.458	0.587	-97.2%	2.039	0.014	-99.3%	0.529
Phase 2 Rural	12.622	0.030	-99.7%	1.244	0.001	-99.9%	0.015
Phase 3 M'way	15.248	0.020	-99.7%	1.004	0.000	-100.0%	0.005
Combined result	15.846	0.171	-98.8%	1.335	0.004	-99.7%	0.145
THC							
Phase 1 Urban	22.260	14.710	-31.2%	19.628	18.187	-7.3%	14.295
Phase 2 Rural	15.519	11.026	-30.1%	14.213	13.659	-3.9%	10.961
Phase 3 M'way	30.297	16.658	-46.6%	24.525	24.194	-1.3%	16.690
Combined result	23.913	14.515	-38.4%	20.619	19.946	-3.3%	14.403

	Modal pre-catalyst	Modal post-catalyst	Catalyst impact	FTIR pre-catalyst	FTIR post-catalyst	Catalyst impact	Bag (post catalyst)
	Mean (g/km)	Mean (g/km)	(%)	Mean (g/km)	Mean (g/km)	(%)	Mean (g/km)
				NOx			
Phase 1 Urban	9.560	2.282	-66.4%	11.950	2.756	-76.9%	2.582
Phase 2 Rural	7.094	2.038	-68.2%	8.732	2.292	-73.7%	2.294
Phase 3 M'way	5.473	0.622	-83.3%	5.966	0.624	-89.5%	0.653
Combined result	7.009	1.466	-72.9%	8.232	1.605	-80.5%	1.632

The first two columns are from the aggregated modal data averaged over the five dual fuel runs, whilst the fourth and fifth columns are the FTIR tailpipe analysis, from the first three runs, and engine exhaust analysis from the final two runs. The impact of the catalyst from these two perspectives are tabulated to the right of these columns. The final columns is the tailpipe bag measurements, again averaged over the five dual fuel runs.

For the dual fuel vehicle additional insight into the impact of the catalyst was obtained from the track driving using the PEMS measurements. From Table 4-10 it is seen that triplicate runs were driven with and without the catalyst present. Table 4-17 presents the results in the same format as in Table 4-16 for the chassis dynamometer testing.

Table 4-17: PEMS results from track testing without and with the catalyst present (dual fuel vehicle)

	Track testing No catalyst	Track testing With catalyst	Change caused by Catalyst
	Mean (g/km)	Mean (g/km)	(%)
		CO_2	
Phase 1 Urban	1804.058	1799.185	-0.3%
Phase 2 Rural	1364.529	1359.280	-0.4%
Phase 3 Motorway	1029.917	1033.142	+0.3%
Combined result	1331.452	1329.856	-0.1%
		CO	
Phase 1 Urban	18.756	0.492	-97.3%
Phase 2 Rural	9.177	0.098	-98.9%
Phase 3 Motorway	2.269	0.009	-99.6%
Combined result	8.628	0.162	-98.1%
		THC	
Phase 1 Urban	12.943	13.784	+7.3%
Phase 2 Rural	8.136	7.093	-12.4%
Phase 3 Motorway	30.128	24.005	-20.3%
Combined result	19.204	16.411	-14.5%
		NOx	
Phase 1 Urban	7.776	5.610	-28.4%
Phase 2 Rural	3.314	2.576	-21.9%
Phase 3 Motorway	1.338	0.864	-35.3%
Combined result	3.612	2.613	-27.7%

The data in the tables show some common themes, but some differences too.

For CO the conclusion is relatively unequivocal: the catalyst is converting more than 97% of the CO to CO_2. An important implication of this is that this reaction will increase tailpipe CO_2 emissions by approximately 25 g/km for the combined cycle, because around 15.7 g of CO are oxidised to CO_2.

For hydrocarbons the conclusion is more complex, with modal and FTIR results giving different impacts. The modal data indicate that around 38% of the THC is oxidised overall, with around 47% being oxidised during the motorway phase of the cycle. The modal tailpipe data agrees well with the bag THC results. Furthermore, the combined reduction in CO and THC emissions from the modal and bag data agree well with the increases in CO_2 emissions.

In contrast, the FTIR methane measurements indicate a much smaller impact from the catalyst. However, the data are inconsistent. When the modal HC from the pre- and post-catalyst FIDs are superimposed and compared with the FTIR engine and tailpipe methane analyses, the latter might be reaching a saturated value. Specifically, for these high methane concentrations during the high speed (motorway) phase the FID shows the tailpipe HC concentration is around 50% lower than the engine out concentration, leading to the observed ~47% reduction caused by the catalyst over the whole Phase 3 assessed using the modal FID data. In contrast the FTIR shows virtually no change.

The FTIR pre- and post-catalyst CO_2 data are also inconsistent and very challenging to understand.

Again it is noted that these measurements are in support of the development of a methane slip test protocol, and it is outside the scope of this study to undertake a detailed inter-comparison of the analytical techniques.

Therefore overall the modal data appears to be the more reliable, and indicates the catalyst is reducing HC levels, which are believed to be predominantly methane, by up to 50%.

For NOx emissions, both the modal and FTIR data indicate a large reduction, 73% overall, and >83% for the motorway driving.

Table 4-17 shows equivalent data measured by the PEMS equipment for track driving with the catalyst fitted, and when it was replaced by a section of empty exhaust pipe. These data are not directly comparable with the chassis dynamometer testing, principally because the vehicle was then loaded to 30 tonnes rather than the 20 tonne simulation on the chassis dynamometer, and inertia and load simulation was replaced by real on the road driving. In terms of the changes measured by the PEMS analysers, the catalyst causes:

- CO – again very large reductions, greater than 97%.
- HC – smaller reductions than seen from the dynamometer testing, typically ~15%.
- NOx – as for the dynamometer testing, typically the catalyst causes marked but smaller reductions, around 30% rather than 73%.

Overall, it is clear the catalyst is having an impact.

4.3.5 Emissions as a function of speed

An important aspect of the protocol is that it will involve collecting methane slip (or THC emissions) over the whole range of speeds from stationary to 90 km/h Regulation 582/2011/EC gives recommendations regarding the weighting of results by speed, namely 20% for the speed range 0 – 50 km/h, 25% for the speed range 50 – 75 km/h, and 55% for the speed range above 75 km/h. An understanding of how methane slip varies with speed provides an indication as to how sensitive the overall assessment of methane slip is to these ratios.

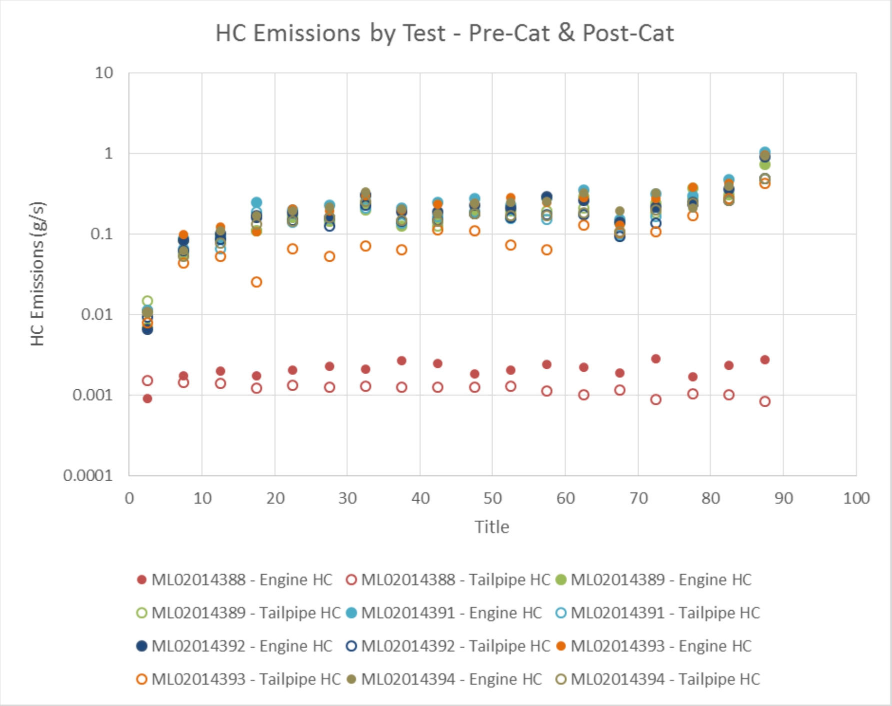
Whilst emissions measurements over a defined cycle may be presented using the metric of g/km, the direct PEMS measurements is of the instantaneous rate of methane emissions, i.e. g/second. Plotting this instantaneous rate of hydrocarbon emissions against speed is very noisy, and it is difficult to discern patterns. Therefore the modal pre- and post-catalyst FID data was analysed using the steps described below:

- The 1800 seconds of each the WHVC chassis dynamometer test was split into 180 consecutive 10 second segments.

- For each of the ten second segments the average HC emissions, and the average speed was calculated.
- Data were then aggregated further by combining all ten second segments within 5 km/h average speed windows, i.e. for 0 – 4.999 km/h, 5.0 – 9.999 km/h, 10.0 – 14.999 km/h etc., and averaging these.

This gives the average emissions for 10 second segments, by speed, for each of the six chassis dynamometer tests, for both pre- and post-catalyst THC. This is plotted in Figure 4-8. Note that the lower pair of data, for run ML02014388, are for the vehicle in the **diesel only mode**. For the other five runs the open circles (tailpipe, i.e. post catalyst data) have slightly lower emission levels than the corresponding engine out data (i.e. pre-catalyst data) but the difference is very small compared with the equivalent data shown in Figure 4-3 where the catalyst is having a much larger impact.

Figure 4-8 – Pre- and post-catalyst THC emissions over the WHVC for the dual fuel vehicle as a function of speed [59]



At this higher level of aggregation the data remain somewhat noisy with small peaks and troughs being seen that are not thought to be statistically significant.

Note the graph in Figure 4-8 is plotted on a logarithmic vertical axis, so the range is around a factor of 20. This is represented in Figure 4-9 on a linear vertical scale for six speed ranges[60].

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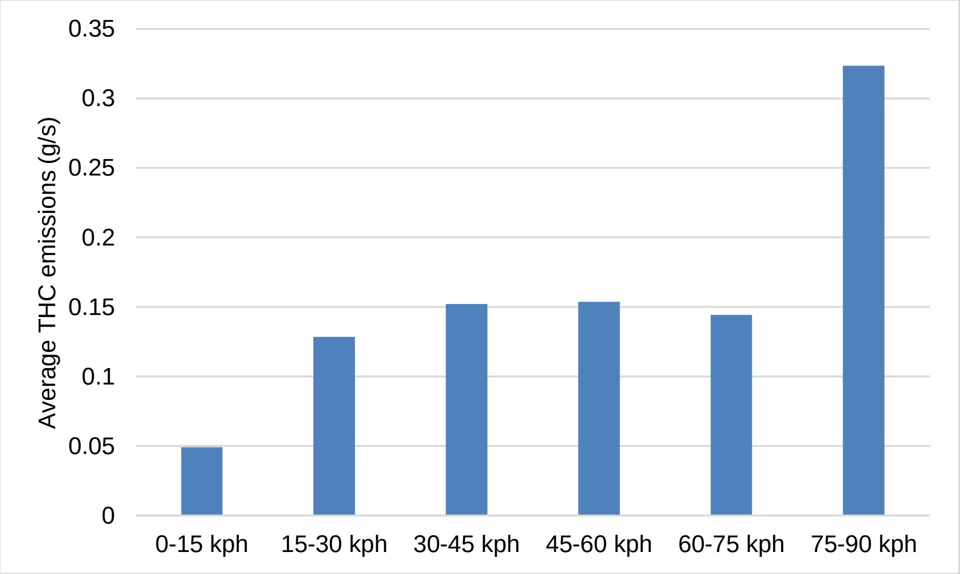
[59] From tab: Emissions vs speed; Workbook: Mercedes Analysis v2.0.xlsx; Folder: C:\Users\John_Norris\Documents\JOHNWORK\PROJECTS\DfT T-TEAR Methane slip ED60231\3 Project Delivery\4 Individual tasks\Task 2\Veh 1 Mercedes Benz-Hardstaffs\Data Analysis

[60] now to right of figure above in the spreadsheet

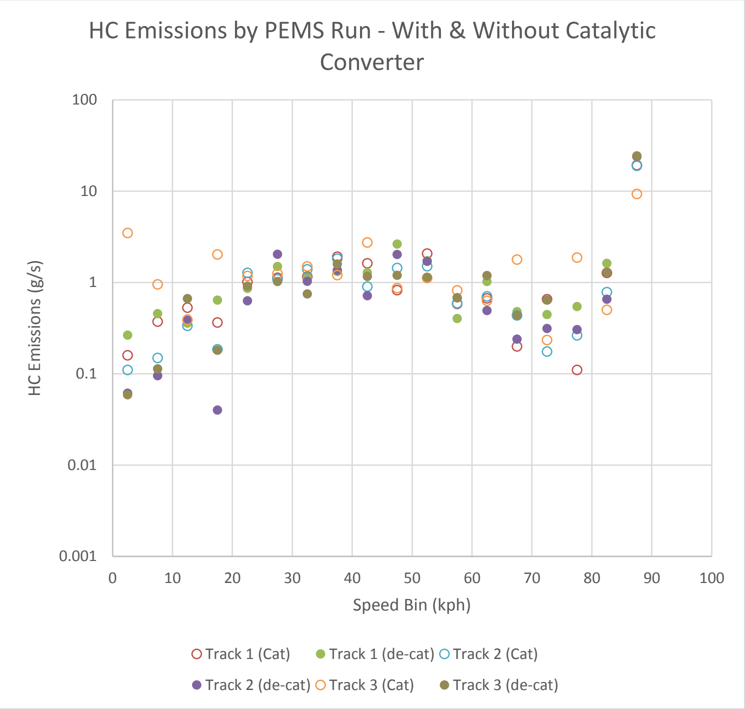
Figure 4-9 – Post-catalyst THC emissions over the WHVC for different speed ranges (dual fuel vehicle)



This graph shows how the emissions per unit time are low for speeds below 15 km/h, high for speeds above 75 km/h, and similar for the wide range between these.

The hydro carbon emissions from track driving for this vehicle, with a vehicle weight of 30 tonnes, are shown in Figure 4-10. This is somewhat similar but there is a notable dip in HC emissions between 60 and 75 km/h, in contract to the emissions seen on the dynamometer.

Figure 4-10 – Pre- and post-catalyst THC emissions over the WHVC for the dual fuel vehicle as a function of speed for track driving



The important message taken from these figures is how HC emissions do vary with speed and with load conditions. Also, they are notably higher for the highest speed range, 75 – 90 km/h. The EC regulation indicates that 55% of the test cycle should be spent at these speeds. Consequently, these data indicate that reducing this would give a lower overall HC emissions measurement. Given the typical on-the-road driving these articulated vehicles undertake, reducing the amount of high speed testing would lead to a systematic difference relative to real world emissions.

4.3.6 Gas substitution ratio

For this dual fuel truck there is an additional dimension to the analysis relative to the dedicated methane truck, namely the relative quantities of diesel and methane used. When compared to operating in diesel only mode this can be described in terms of how much diesel is being substituted by methane. This is a variable. Studies by M Stettler at the University of Cambridge have shown, and are supported by general information from Hardstaff, that this substitution ratio:

- Is low, or zero, when the engine is cold;
- Is low, or zero, at idle and for low powers;
- Rises with increased power requirements up to a threshold; and
- Reduces for the highest power requirements.

This gas substitution ratio (GSR) can be measured using several methods:

1. Over a long period of operation by noting the diesel fuel and methane fuel added to the vehicle's fuel tanks. This is the method used in the Low Carbon Truck Trial.

2. When the vehicle was tested by Millbrook it was fitted with a JPS Engineering fuel flow meter. This gives a pulse/count for every 5 mls of diesel fuel used, which was logged together with other data from the vehicle.

3. From the gas analysers the amount of carbon leaving the tailpipe can be calculated, summing the CO_2, CO and HC emissions. The difference between the total carbon emitted and the carbon consumed as diesel fuel comes from the methane fuel. **From these data the gas substitution ratio can be calculated and expressed in terms of the source of the carbon leaving the tailpipe.**

The GSR based on the origin of the carbon was calculated as part of the data analysis. Table 4-18 gives the results of this analysis for the dynamometer studies as calculated from the diesel fuel meter and the bag data, and from the PEMS equipment (each being the average of five runs). The lower part of the table gives the results for the track testing, with and without the catalyst being present (each being the average of three runs).

Table 4-18: Gas substitution ratios (GSR) for the dynamometer studies from the bag data, PEMS equipment

	Bag		PEMS	
	Average GSR	Standard Deviation	Average GSR	Standard Deviation
	Dynamometer (post-catalyst)		**Dynamometer (post-catalyst)**	
Phase 1 Urban	25.54%	5.55%	25.78%	6.63%
Phase 2 Rural	35.55%	1.05%	34.72%	4.10%
Phase 3 Motorway	54.93%	1.15%	55.39%	1.15%
Overall	39.46%	1.66%	39.56%	2.99%
	Track with catalyst		**Track without catalyst**	
Phase 1 Urban	38.38%	1.76%	37.23%	3.11%
Phase 2 Rural	45.09%	3.79%	45.57%	4.90%
Phase 3 Motorway	61.70%	2.74%	62.01%	1.78%
Overall	48.88%	1.84%	48.75%	2.77%

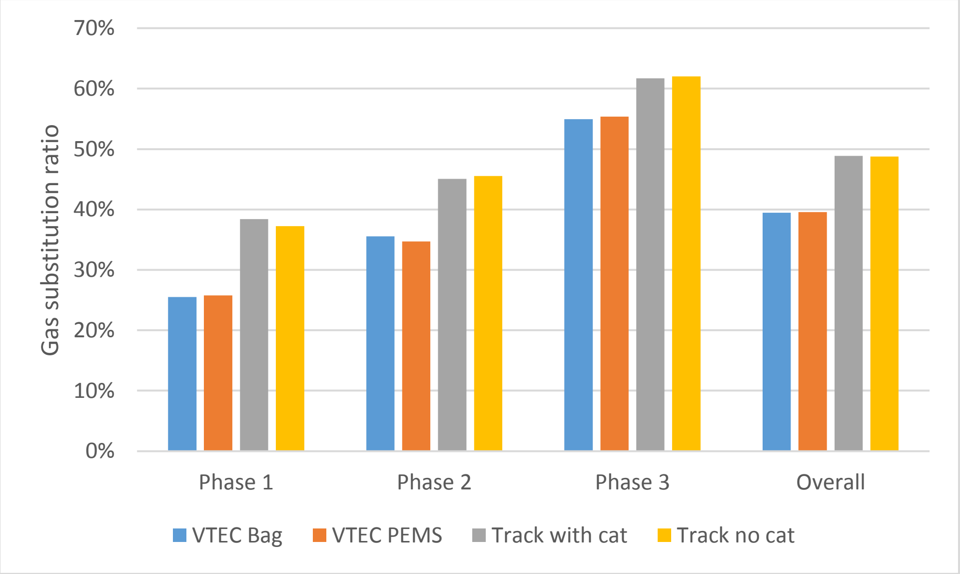
This is shown graphically in Figure 4-11, phase by phase.

From these data it is noted:

- GSR increases from Urban to Rural and on to Motorway, as the average speed of the WHVC increases;
- There is excellent agreement between both the GSR calculated from the bag analysis and PEMS equipment for the chassis dynamometer testing;

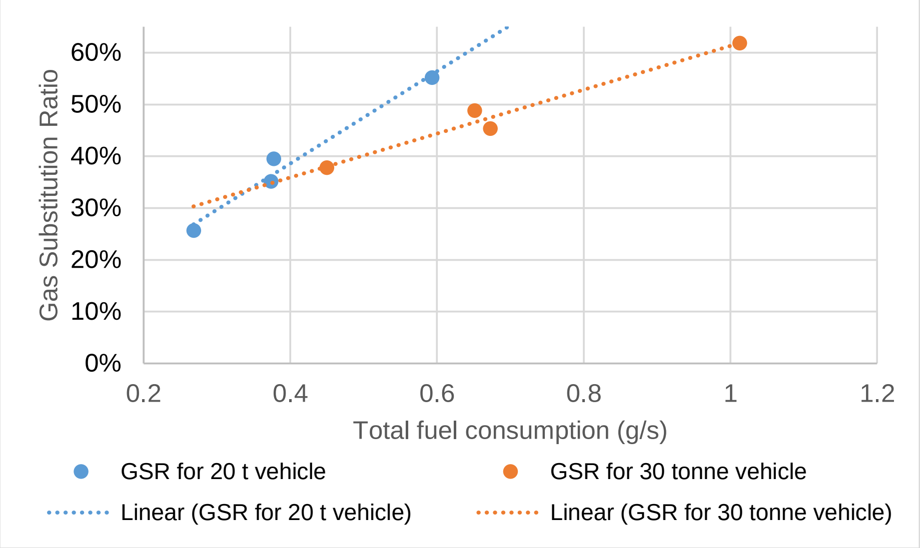
- There is excellent agreement between the GSR calculated from the PEMS analysis for when the vehicle was fitted with the methane slip catalyst, and when it was removed; and
- There is a systematic increase in the GSR between the dynamometer testing, simulating a vehicle weighing 20 tonnes, and the track testing when the vehicle's weight was 30 tonnes.

Figure 4-11 – GSR for dynamometer and track testing, by WHVC phase (dual fuel vehicle)



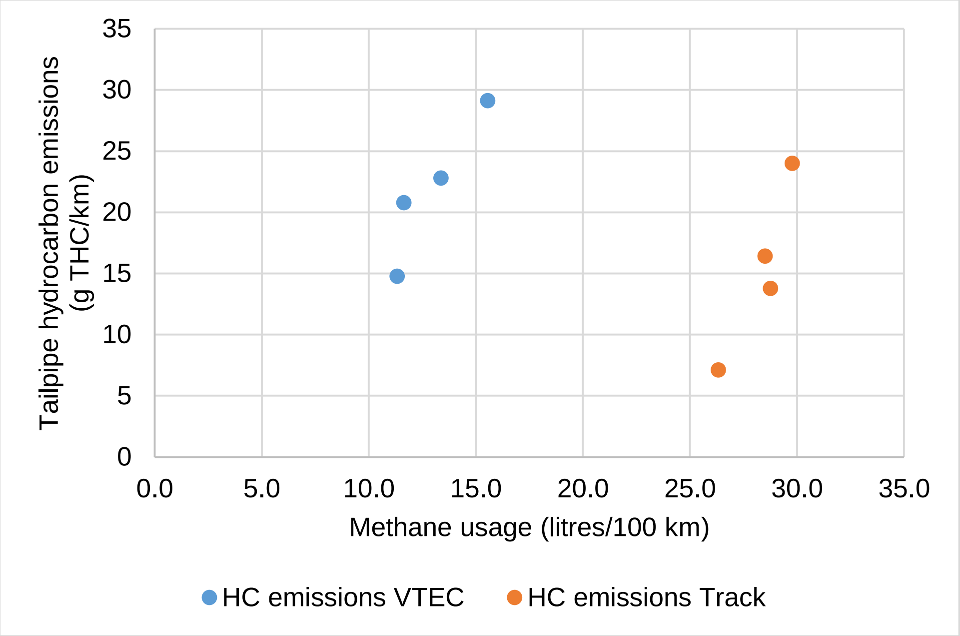
There is not a simple relationship between the total fuel used and the GSR; the mapping is more sophisticated than this. Phase 3 has the highest rate of total fuel usage (mass per second), although this is not the case when expressed in terms of fuel usage /km travelled. The graph below shows the fuel consumption rates and the gas substitution ratios. At first sight there does appear to be a simple relationship, but when the data are sub-divided into the two series of tests for the 20 tonne vehicle (tested on the dynamometer) and the 30 tonnes vehicle tested on the track, it is seen that no simple relationship exists for all the data.

Figure 4-12 – GSR plotted against total fuel consumption



More importantly for this project is the subject of methane slip. Using the GSR calculated as described above, and the total fuel used, the tailpipe hydrocarbon emissions can be plotted against methane consumption. This is done in Figure 4-13.

Figure 4-13 – Tailpipe hydrocarbon emissions plotted against methane usage (dual fuel vehicle)



Both the methane fuel consumption and the hydrocarbon emissions are expressed in terms of quantity per distance travelled (as reported by Millbrook). The tailpipe HC emissions were measured by PEMS whilst the methane usage was calculated from the PEMS data. Consequently, both data sets are drawn from a consistent raw data set.

The important message from this figure is that there is **no simple relationship between the hydrocarbon (presumed methane) emissions and the methane fuel consumption rate.** This was anticipated, and is consistent with other studies, e.g. those undertaken at the University of Cambridge. It underlines the importance of this study **to develop a methane slip protocol for a cycle representative of real world usage patterns**, rather than take a few measurements at, for example, selected speeds and be able to infer the performance of the vehicle.

4.3.7 Emissions during on the road (track) driving

The PEMS results from the VTEC tests, where the catalyst was always present, can be compared with the PEMS results from the track driving when the catalyst was present. However, it should be noted that the two sets of results were obtained from the vehicle tested at different weights. The chassis dynamometer testing was at an inertia (equivalent vehicle weight) of 20.0 tonnes whilst the track testing occurred with the tractor unit linked to a semi-loaded curtain trailer, such that the weight of the whole combined unit was 30.2 tonnes.

Table 4-19 summarises the data collected using PEMS only for these two groups of emissions tests.

Table 4-19: Dynamometer (VTEC) vs Track testing (dual fuel vehicle, at different weights)

Measure	PEMS VTEC tests Test mass ~20 tonnes		PEMS Track tests Test mass ~30 tonnes		Ratio track to VTEC
	Mean (g/km)	Stdev (%)	Mean (g/km)	Stdev (%)	
THC					
Phase 1 Urban	20.789	1.6%	13.784	3.2%	66%
Phase 2 Rural	14.772	3.1%	7.093	5.7%	48%
Phase 3 Motorway	29.133	1.7%	24.005	1.5%	82%
Combined result	22.791	1.7%	16.411	0.5%	72%
CO_2					
Phase 1 Urban	1281.4	1.8%	1799.2	0.4%	140%
Phase 2 Rural	877.0	1.3%	1359.3	0.7%	155%
Phase 3 Motorway	728.9	2.3%	1033.1	0.1%	142%
Combined result	916.0	1.8%	1329.9	0.0%	145%
NOx					
Phase 1 Urban	3.182	19.3%	5.610	9.9%	176%
Phase 2 Rural	2.824	4.5%	2.576	1.3%	91%
Phase 3 Motorway	0.878	5.8%	0.864	10.4%	98%
Combined result	2.044	9.4%	2.613	7.7%	128%

Some comments on these data are:

- Within a group of tests reproducibility is generally good, with the standard deviation of measurements being less than 2.5% for CO_2 and less than 6% for HC;
- For CO_2 there are significant increased emissions for track testing, emissions being 145% for the whole cycle. This is shown in Figure 4-13 and is virtually independent of average speed, which is a distinctly different pattern than was seen for the dedicated methane vehicle (see Figure 4-6). This is primarily a consequence of the heavier road load and the probable approximations/inaccuracies on the chassis dynamometer load used;
- For HC, in contrast, there is a decrease in emissions for track driving for all phases; and
- NOx emissions, shown in Figure 4-14 with the HC emissions, are variable with phase 1, more stop/start driving, giving an increase, whereas there is little change for phases 2 and 3.

Figure 4-14 – CO_2 emissions from chassis dynamometer and track testing (dual fuel vehicle, at different weights)

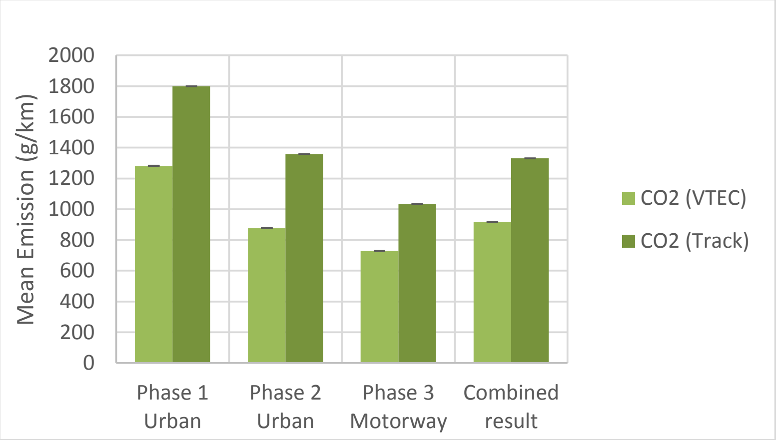
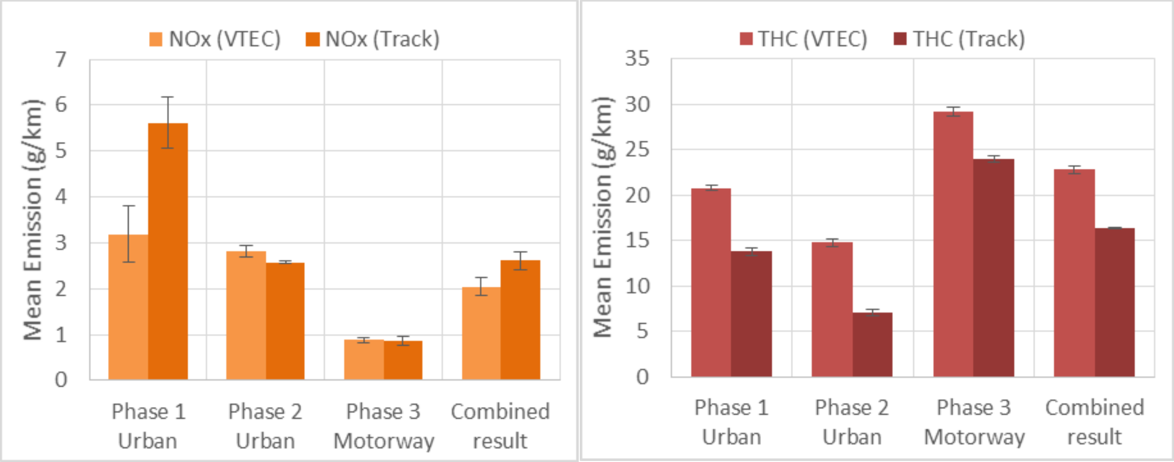


Figure 4-15 – NOx and THC emissions from chassis dynamometer and track testing (dual fuel vehicle, at different weights)



Overall, it is a complex pattern. In the context of this project's objectives, quantifying methane slip against CO_2 savings, Figure 4-12 and Table 4-17 show that the vehicle's performance varies, and there are distinctly lower emissions for the track driving and the higher load. Relative to chassis dynamometer testing, track cycles used nearly twice as much methane (see Figure 4-12) and produced around 75% of the HC emissions (see Figure 4-15). Therefore, in terms of HC emissions relative to CO_2 abated, the vehicle produced around 37.5% on the track relative to on the chassis dynamometer over the WHVC.

4.3.8 PM emissions

No second by second measurement of PM was possible using the standard analysis suite, nor was PM measurement part of PEMS capability for the system used. Therefore only single data points are available (albeit disaggregated by drive cycle Phase) for each VTEC test, and there was no track test data. These are reported in Table 4-15.

Also, the values obtained are small, and have a relatively high level of uncertainty. For the dual fuel data relative to the vehicle operating in diesel only mode, there is a pattern suggesting a small rise in PM emissions for the Urban and Rural phases and a small reduction in PM emissions for the Motorway Phase. Overall, the dual fuel vehicle gives a 15% increase relative to the diesel only run. However, this is less than the standard deviation of the data and, therefore, on the basis of the data available, the conclusion has to be that **no statistically significant difference was observed.**

4.3.9 The effect of referencing to CO_2 emissions

The project's focus is to measure methane slip under representative vehicle operating conditions, so that not only changes in CO_2 but also changes in GHG emissions can be assessed.

Generally, replacing some diesel with methane leads to lower CO_2 emissions. Typically it was reported in the Low Carbon Truck Trial First Annual Report, that the average substitution ratio was 46% and that the average CO_2 savings were 9%. In round figures this means that around 1% CO_2 savings were generated for each 5% GSR ratio. The quantity of methane slip that would cancel this out is given by equation 1 below:

Methane emissions (g) $= CO_2$ emissions * 0.2 * GSR /28

The factor of 28 comes from the GWP of methane, i.e. that 1 g methane emissions is assumed, for the purposes of this study and based on the latest scientific evidence, equivalent to 28 g CO_2 emissions.

The important factors in Equation 1 are:

- CO_2 emissions – to be measured; and
- GSR.

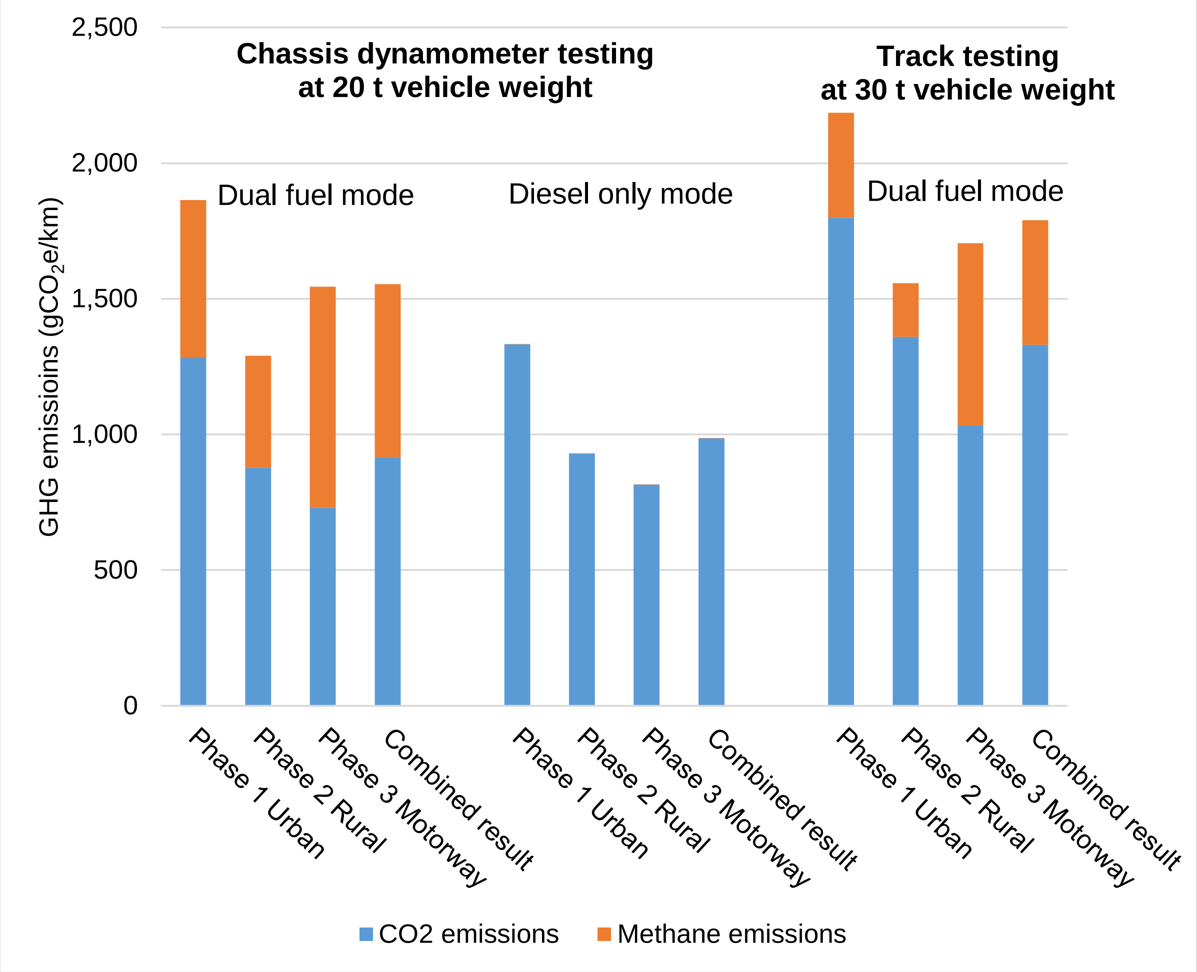
GSR could be taken as 46% for whole project average or from the fleet's monitoring data the average GSR for the fleet, or even the vehicle, being assessed.

Therefore, it is important that the methane slip measured is referenced/normalised to the CO_2 emissions during the cycle.

4.3.10 Overall GHG emissions

The CO_2 and methane emissions (using THC measurements as a proxy for methane) can be combined to give overall GHG emissions. Figure 4-16 shows these GHG emissions for the vehicle when tested on the chassis dynamometer, at the light load of 20 tonnes in both its methane/diesel and diesel only modes, and when the vehicle was tested on the track in methane/diesel mode, at the heavier load of 30 tonnes. Data are shown for the three components of the WHVC and the combined cycle.

Figure 4-16 – The greenhouse gas emissions from the dual fuel articulated truck in both dual fuel and diesel only fuelling modes when tested on the chassis dynamometer and in only dual fuel mode when tested on the track, over the three phases of the WHVC



Data from the vehicle operating with diesel only fuelling occurred for the chassis dynamometer testing but not for the track testing. Therefore the central four columns (the results for a single diesel only mode) should only be compared with the dual fuel running on the left of the figure. It is seen that in diesel only mode there is negligible GHG emissions contribution from the methane, whereas in dual fuel mode the methane emissions contribute markedly to the overall GHG emissions. The CO_2 emissions in diesel only mode are higher than in dual fuel mode. This is most easily seen for the combined result where in diesel only mode the CO_2 emissions are just below 1,000 g CO_2/km, whereas in dual fuel mode they are considerably below the 1,000 g/km line. Therefore, when operating in dual fuel mode there is a CO_2 saving, relative to the diesel comparator. However, for this vehicle the 22.7 g/km methane emissions lead to a further 638 gCO_2e/km emissions, **i.e. the methane emissions**

cause the vehicle's overall GHG emissions to increase by 58%, despite the 7% reduction in CO_2 emissions.

By way of a comparison with an independent assessment of CO_2 emissions, the standard CO_2 emissions for a 30 – 40 tonne Euro V articulated truck, with 50% loading on a flat road is 1,008 g CO_2/km at 40 kph (the average speed over the combined WHVC) from the emissions factors given in the EMEP/EEA Emission Inventory Guidebook for 2013[61]. This is close to the value measured (983 g CO_2/km) on the chassis dynamometer.

Again it is emphasised that this study is not about making measurements on a specific methane fuelled vehicle to judge its GHG savings, but about developing an appropriate test protocol. The key message to be taken form the testing of the dual fuel vehicle are:

- Firstly that overall the test protocol does provide the measurements required to assess changes in GHG emissions as demonstrated on a vehicle that had significant methane emissions, and
- Secondly, it emphasises the importance of taking measurements in the diesel only mode. This is pivotal to the accurate determination of the change in GHG emissions in the dual fuel mode relative to its diesel comparator.

4.4 The reliability of testing

4.4.1 Variability observed

Previous sections of this chapter have considered the absolute (and relative) values measured. This section considers specifically the reliability of testing.

A starting point is the general acceptance that testing in triplicate using standard bag or modal analysis on a chassis dynamometer represents "best practice" for obtaining a high level of reproducibility. This is used as the standard against which alternative analysis techniques, i.e. PEMS, and drive cycles are assessed.

It was noted in Section 3.5 that the reliability of testing is not dependent on a single factor, rather it varies according to:

a. The size of the parameter to be measured;

b. The accuracy with which the parameter can be measured by the analysis technique;

c. The accuracy with which other parameters required in the data processing can be measured by their analysis techniques;

d. The variability of the parameter of interest with uncontrolled aspects of the test protocol;

e. The size and variability of any background interfering signal; and

f. The accuracy required for the measurement of the parameter of interest.

The pilot vehicle testing provides an independent assessment of factors b) and c) above for the draft test protocol.

Independent test houses have over a period of decades developed chassis dynamometer testing such that for CO_2 emissions a series of three runs would be expected to have a standard deviation of less than 1% over a regulatory cycle or its equivalent. For pollutants it would be higher for the smaller signal, increasing in percentage terms as the average value decreases. For the proposed test protocol important questions are:

- What is the variability of the combination of testing procedure and analysers recommended? and
- What is the variability of the testing procedure and the accepted "best" analysis method?

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[61] Available from http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

In this vehicle testing programme we collected data using the standard regulatory bag process on a chassis dynamometer and using PEMS equipment for both chassis dynamometer and track testing. The results are given in Table 4-20 for the dedicated methane vehicle, and in Table 4-21 for the dual fuel vehicle.

Table 4-20 - The standard deviation of different measurement techniques over different drive cycle segments for the dedicated methane vehicle

	Bag		PEMS	VTEC	PEMS	Track
THC measurements	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
WHVC Phase 1 (Urban) only	0.219	3.87%	0.444	20.95%	0.219	21.26%
WHVC Phase 2 (Rural) only	0.260	12.92%	0.356	22.60%	0.228	15.15%
WHVC Phase 3 (Motorway) only	0.801	7.80%	0.925	14.41%	0.163	1.85%
Whole WHVC	0.490	7.55%	0.632	16.50%	0.197	11.05%
CO$_2$ measurements	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
WHVC Phase 1 (Urban) only	1,214.1	2.45%	1449.2	2.11%	1384.2	1.56%
WHVC Phase 2 (Rural) only	855.0	1.20%	991.0	2.22%	878.2	1.36%
WHVC Phase 3 (Motorway) only	757.6	1.01%	871.8	1.69%	703.5	0.89%
Whole WHVC	907.0	1.46%	1,059.7	1.69%	703.5	0.89%
NOx measurements	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
WHVC Phase 1 (Urban) only	1.938	11.83%	2.720	9.08%	0.780	15.44%
WHVC Phase 2 (Rural) only	0.631	11.43%	0.858	9.01%	0.620	19.56%
WHVC Phase 3 (Motorway) only	0.090	16.96%	0.142	8.63%	0.121	18.24%
Whole WHVC	0.737	10.23%	1.034	7.97%	0.441	17.12%

These show that:

- For CO$_2$ there is little difference between the standard deviation of bag measurements of separate phases of the WHVC and the whole cycle;
- The actual standard deviation of bag CO$_2$ measurements ranged from around 1% for the dedicated methane vehicle to around 0.3% for the dual fuel vehicle; and
- For the PEMS data, ignoring the systematic differences discussed earlier, the standard deviation of PEMS CO$_2$ measurements on the chassis dynamometer, that are directly comparable to the bag measurements, ranged from around 1.5% for the dedicated methane vehicle to around 0.6% for the dual fuel vehicle, (i.e. these values were 1.5 to 2.0 times larger than for the bag measurement).

For THC it was noted that smaller emission values led to larger errors. More specifically:

- For the dedicated methane vehicle where the mean THC emissions were around 1 g/km, the error from the bag measurements was around 8% whereas for PEMS it was around 12%; and
- For the dual fuel vehicle, with much higher THC emissions, the mean emission rate was around 20 – 25 g/km, the error from the bag measurements was around 7% whereas for PEMS it was around 3%.

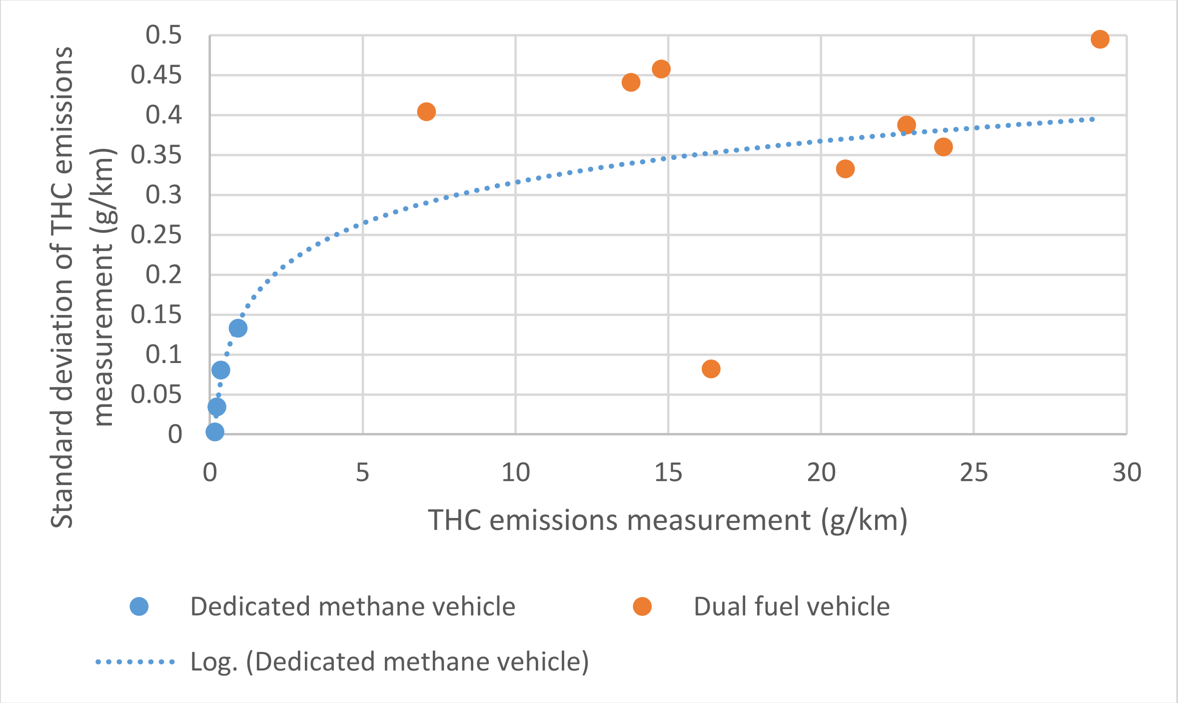
The comments above express the error in terms of a percentage of the average measurement value. An alternative is to consider the absolute values of the error. A graph of this uncertainty (standard deviation over three measurements) in the PEMS THC measurement, as a function of the actual THC signal is given in Figure 4-17.

A log fit is also put through the data. These indicate that at the 2 g/km and 4 g/km emission levels the standard deviation of the PEMS measurements of three runs would be 0.20 and 0.25 g/km respectively, or 10% and 6%.

Table 4-21; The standard deviation of different measurement techniques over different drive cycle segments for the dual fuel vehicle

	Bag		PEMS VTEC		PEMS Track	
	20 tonne vehicle weight				30 tonne vehicle weight	
THC measurements	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
WHVC Phase 1 (Urban) only	14.295	34.04%	20.789	1.55%	13.784	3.18%
WHVC Phase 2 (Rural) only	10.961	9.99%	14.772	3.10%	7.093	5.66%
WHVC Phase 3 (Motorway) only	16.690	6.19%	29.133	1.70%	24.005	1.50%
Whole WHVC	14.403	14.20%	22.791	1.68%	16.411	0.45%
CO_2 measurements	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
WHVC Phase 1 (Urban) only	1,095.9	0.48%	1,281.4	1.82%	1,799.2	0.42%
WHVC Phase 2 (Rural) only	759.4	0.33%	877.0	1.25%	1,359.3	0.67%
WHVC Phase 3 (Motorway) only	613.8	0.68%	728.9	2.26%	1,033.1	0.10%
Whole WHVC	781.9	0.33%	916.0	1.78%	1,329.9	0.03%
NOx measurements	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
WHVC Phase 1 (Urban) only	2.582	18.57%	3.182	19.28%	5.610	9.90%
WHVC Phase 2 (Rural) only	2.294	5.03%	2.824	4.46%	2.576	1.25%
WHVC Phase 3 (Motorway) only	0.653	8.15%	0.878	5.85%	0.864	10.39%
Whole WHVC	1.632	9.09%	2.044	9.37%	2.613	7.70%

Figure 4-17 The absolute standard deviation of triplicate measurements plotted against the average value of the measurements



For NOx measurements the error in relation to the measured value follows a similar pattern to that for THC.

- Generally where average emissions are around 1 g/km the standard deviation of the measurements is around 10% for bag measurements;
- The standard deviation of the PEMS measurements is similar, around 10%; and
- However, for the dedicated methane vehicle when tested on the track NOx emissions were much lower, around 0.4 g/km, and the standard deviation of the data collected was around 20%.

Interestingly, these NOx data follow nearly the same standard deviation – emissions measurement profile that are shown in Figure 4-17. The above dotted line predicts a 20% error at 0.4 g/km but suggests the error for around 1 g/km would be 14%, rather than the 10% observed.

4.4.2 Implications for the test protocol

Generally it was noted that the errors associated with PEMS measurements are around 1.5 times higher than for the equivalent bag analysis.

The standardised protocol appears to be a totally valid approach for track PEMS testing. The protocol consists of:

- Undertaking three separate runs;
- Comparing to identify outliers, and exceptionally where they occur, removing that data point; and
- Taking means of the “valid” runs.

Examination of the data collected showed that the PEMS errors associated with the proposed test cycle are at least comparable to the errors observed for the whole WHVC. In a number of cases they were lower because Phase 1 of the WHVC can have larger errors associated with it, and its removal from inclusion in the test cycle improved reliability.

In this application, seeking to measure methane slip, it could be estimated that:

a. The size of the signal to be measured is the amount of methane emissions that would negate the GHG emissions reduction caused by lower CO_2 emissions. For the dual fuel vehicle on the track with around a 30 tonne vehicle weight, typically CO_2 emissions are around 1,300 g/km.

b. The Low Carbon Truck Demonstrator trial Year 1 report indicates average substitution ratio[62] is around 46%, and CO_2 emissions savings are 9% (This would give CO_2 savings of 117 g/km for this truck's activity).

c. The level of methane emissions to counteract the CO_2 reductions above would be 1.86 g/km for a 4% CO_2 reduction and 4.18 g/km for a 9% CO_2 reduction.

d. The THC emissions from the vehicle in its diesel only mode was 0.11 g/km over the whole WHVC, and 0.065 g/km over phases 2 and 3 (Rural and Motorway).

e. The required measurement is thus a signal of 29 or 64 times the background.

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[62] In the First Annual Report the substitution ratio is defined as "the percentage of diesel fuel replaced by gas".

5 Stakeholder Workshop

5.1 Overview and objectives of the workshop

Ahead of finalising the recommendations for the wider testing of vehicles and equipment, the proposed test protocol to be used was discussed with principal stakeholders. A central activity in this process was the organisation and delivery of a stakeholder workshop, to present ideas, and to listen to feedback. In addition to gaining wider understanding and acceptance of the methane slip test protocol, a further objective was to develop a better test protocol through listening to and discussing with the principal stakeholders, learning from their considerable and relevant experience.

A stakeholder Workshop was held on Friday 20th March 2015, using one of the smaller conference venues at Millbrook Proving Ground. Stakeholders invited were representative of the following groups of organisations:

- Vehicle OEMs;
- Dual fuel aftermarket vehicle converters
- Vehicle catalyst manufacturer;
- Methane fuel filling station providers;
- Vehicle testing organisations;
- Fleet operators;
- Association representing the automotive manufacturers and traders;
- Associations representing the freight operators;
- Management of the Low Carbon Truck Trial test programme; and
- Researchers involved in investigating the science of the operation of methane fuelled vehicles.

The organisation was hosted by the Ricardo-AEA consortium, and the DfT Freight Logistics Team. The principal agenda items were:

Presentation	Topic	Lead organisation
Presentation 1	Overview of the need for the project and desired outcomes Intended use of the test protocol in the future and its link to DfT Policy formation	DfT DfT
Presentation 2	Summary of project, its tasks and the scope of the evidence collected	J Norris (Ricardo-AEA)
Presentation 3	Presentation of Draft test protocol	J Norris (Ricardo-AEA)
	Discussion of Draft test protocol	All
	Future testing programme using the test protocol	DfT
	Summary of key points agreed, decisions, and follow up actions	J Norris (Ricardo-AEA) & DfT

5.2 Presentation by DfT on the need and intended use of the draft test protocol

Key messages from Presentation 1, The DfT Freight Policy overview of the need for the project, its desired outcomes and the intended use of the test protocol in the future and its link to DfT Policy formation, were:

- Interim results of Low Carbon Truck Trials indicated that vehicles running on used cooking oil give significant CO_2 savings, but for gas vehicle performance the GHG savings less clear; because of methane slip, Euro V vs VI, gas availability, dedicated vs dual-fuel vehicles;
- A challenge arises because methane is itself a potent greenhouse gas;
- The Department would like to increase the evidence base around methane slip from HGVs, specifically to quantify the amounts of methane expelled from HGVs during a typical drive cycle, why this occurs, how it can be minimised and what the impacts are on overall greenhouse gas emissions;
- This scoping project has developed a methodology for carrying out emissions testing on HGVs, with a view to a further project to carry out testing using that methodology later in 2015;
- It is intended to be forward-looking, so needs to take account of changing market, e.g. Euro VI; and
- It is not intended to be any form of in-use/compliance test for all gas vehicles.

This overview clearly stated from the DfT sponsor’s perspective what the objectives of the project were and how it was intended the test protocol developed would be used.

5.3 Presentations by Ricardo-AEA covering the project’s structure and the draft test protocol

Presentation 2 gave an overview of the project’s structure and the extent of its research. It succinctly summarised the three phases of the project including further details regarding the scope of Task 1 (the literature review) and Task 2 (the experimental test programme).

Agenda item 4, Presentation 3, gave an overview of the draft test protocol devised, in terms of Figure 3-12 and the eight test protocol components listed in Section 3.6, and reviewed in Section 4.4. The slides contained a complete summary of the revised test protocol described in Section 4.4. This presentation was given as a relatively rapid overview of the draft test protocol, with a detailed slower run through, with discussion occurring as Item 5 on the agenda.

5.4 Discussion of generic subjects

As might be expected with the relatively diverse range of stakeholders present a wide range of views was expressed. These can, to some extent be grouped into themes, covered in the following sub-sections.

5.4.1 How will the proposed test be used?

This issue was high on the agenda of the OEMs. Possibilities they identified include:

- Backward looking, to assess the methane emissions of the Euro V methane consuming vehicles actually on the roads now; and
- Forward looking, to assess methane emissions of the Euro VI methane consuming vehicles which are being developed.

The follow-up comment was to encourage DfT to look forward, rather than testing the existing relatively small fleet currently available. However, there is then the observation that all new vehicles could be type approved. Two different types of vehicle sources were identified:

- OEM-built methane consuming vehicles. It was indicated that these will comply with the type approval regulations, which include measurements of direct methane slip for both dedicated methane and dual fuel vehicles, durability of emissions etc. It was noted that because the technologies used are developing those used can vary between different types of vehicles. For example, the OEM might view the methane slip catalyst as a "service item" to be replaced at specified intervals.
- Retro-fit vehicles where, in particular dual fuel adaptations are made to homologated Euro VI diesel HDVs. The question raised was to what extent the regulations that are currently in force will be used for these vehicles.

A corollary to this is the observation that the test protocol could be used as a tool to indicate key aspects of the cost effectiveness of testing retro-fit methane vehicle conversions. Another important factor is the numbers of vehicles being put onto the road.

5.4.2 How great is the need/appetite for on the road testing?

This issue was raised by those involved in vehicle testing. It was noted that considerable detail was given on a methodology to analyse road testing. It was questioned whether in practice this was necessary. Any testing using PEMS would require such equipment to be fitted to a test vehicle, and an instrument operator to be present in the truck cab during the test. It was questioned whether this was feasible when the vehicle was actually working, on the road, or whether track testing might be the preferred option for most cases.

A counter argument was that there are some large haulage companies who are based far from test tracks. However, it was also noted that some of these key companies have a network of depots, some of which are very close to test tracks.

It was also noted that there is something of a false assumption that road testing equates with markedly lower accuracy. There are some roads that are sufficiently quiet such that they are nearly equivalent to a test track.

Another important point raised in this debate was the valid observation that track testing is already undertaken, is well characterised, and the accuracy achievable is well known. The resulting metric, mass emitted per km travelled is familiar. It is also directly suitable for scenario assessment, where the impact of vehicle-km driven is simply assessed. In contrast, average emissions expressed in mass per unit time are not familiar units.

5.4.3 How will the change in CO_2 relative to a comparator vehicle be estimated?

It was noted that the key driver to this project is the need to gather an evidence base regarding the GHG emissions of methane fuelled vehicles relative to comparable diesel only alternatives. For dual fuel vehicles this involves calculating the change in CO_2 emissions on going from the diesel comparator to the methane vehicle as well as measuring the additional methane emissions. There was considerable discussion regarding how the change in CO_2 emissions might be measured or estimated.

A Cenex representative, managing aspects of the Low Carbon Truck Trial said that the CO_2 savings are known at sponsored fleet/project level (these are aggregated in the final report). For some fleets they will be known at the vehicle level. A counter argument was that it would be good to assess this for the individual vehicle whose methane emissions were being measured. However, this was not universally accepted.

The choice of how this change in CO_2 emissions will be assessed is critical to some details of the test protocol. This is discussed in the following section.

5.5 Discussion of specific aspects of the test protocol

The sub-sections below give an indication of the discussions within the workshop with regard to the different facets of the test protocol.

The vehicle:

- It was agreed that testing should be undertaken on whole vehicles.
- With regards to loading, the draft protocol presented by Ricardo-AEA suggested 50-60% of their payload (consistent with Reg. 582/2011/EC).
    - It was agreed that loading should definitely be over 50%, however, questions were raised regarding the upper limit, including whether there should be one.
    - As far as possible, realistic/real world loads should be used.
    - However, the issue of using exactly the same load every time was also raised, to ensure tests were comparable (reducing variability, and ensuring repeatability).
    - It was agreed that 50% to 60% payload weighting would normally be appropriate.

Fuel:

- The draft test protocol presented suggests that diesel in dual-fuelled vehicle should conform to EN 590 and the methane and ethane content of gaseous fuels should be known.
- Some stakeholders wanted to know why it was necessary to determine the composition of the gaseous fuel and how that would affect the test/its results. It was noted that this was mainly to help understand the test results, e.g. if all elements remained constant with the exception of the fuel used, then this could be a contributing factor to methane slip.
- It was agreed that the quality of the fuel should be known. However, it was noted that composition and quality of gas fuel can vary significantly.
- Methane fuel suppliers indicated that it was not possible to determine the composition for each fill because of the multiplicity of sources used to supply the bunker tanks, and fractionation affecting, for example the methane/ethane ratio as an LNG tank is used.
- For each vehicle tested, it was recommended that a gas sample should be taken and sent for analysis, to identify the gas composition. It was reported this would be relatively inexpensive.
- An employee of a vehicle after-market converter explained how changes in fuel quality could lead to constant methane emissions by causing changes in engine efficiency and in the gas substitution ratio. However, that would vary according to the detailed fuelling strategy used by different dual fuel conversions.

Road or dynamometer:

- The draft test protocol presented suggested that either road or track driving should be used (dynamometer testing is not universally applicable, and not suitable for the heavier vehicles and their payloads).
- Although track testing was preferred by workshop attendees, it was noted that track availability can prove challenging (e.g. fleets operating within certain areas of the country will have difficulty accessing appropriate tracks).
- It was noted that there may be problems with road testing and producing suitable comparators. It is also likely to take a lot longer that other methods of testing due to the need for multiple test repeats to overcome reliability issues.
- It was suggested by some that road testing would provide the most ‘real-world’ conditions.
- However, it was generally agreed that track testing is preferred, not least because at present the results and reliability of road testing are currently unproven.

Driving cycle:

- It was suggested by a number of stakeholders that where driving cycles exist, these should be used during testing.
- Identical tests would be preferred for both diesel and dual-fuel, to ensure repeatability/ comparability.
    - It was agreed that vehicles should be tested for the same length of time in each fuel mode (rather than a longer period for dual fuel).
    - It was agreed that the suggested testing time (2.5 hours) was too long, and the PEMS battery supply was unlikely to last for the duration, so this should be reduced accordingly.
    - It was also suggested that a number of shorter tests should be undertaken, and then repeated (e.g. diesel only, dual fuel, diesel only, dual fuel etc.) to account for

differences once engine is warmed up etc. So perhaps instead of three, 40 minute test cycles, six, 20 minute cycles (2 of each) might be preferable, for example.
    - The question of how many repeats would be necessary was raised, as vehicles can be programmed to adapt/evolve. This would imply that whilst the test needs to be repeated a number of times to obtain an indication of reproducibility and to identify outlying data, e.g. caused by a DPF (Diesel Particulate Filter) regeneration, too many repeats might well be counter-productive.

Other aspects:

- Usage (typical duty cycle) of the test vehicle(s) could be considered
- Stakeholders enquired as to how the diesel baseline would be created.
    - It was initially suggested that there would be a diesel vehicle, and a diesel conversion vehicle – the latter run in both diesel only and dual fuel modes. The dual fuel vehicle would be run in diesel mode and then dual fuel mode, and measurements would be taken when running in both modes.
    - It was suggested that the Low Carbon Truck Trial could provide good comparator diesel vehicles (baseline standard diesel vehicle on a cycle).
    - Also, ‘direct comparators’ would be difficult to identify/define due to huge variability in power, make, model etc. of trucks.

Issues relating to practicalities of testing:

- From the operator’s perspective, it was suggested that they might be willing to spare vehicles for testing providing that they were compensated for this.

Other comments / issues raised:

- If real-world data (road testing) is collected and compared to existing cycles, this is something that has not been done before, and thus there may be an opportunity to strengthen the existing evidence base.
- The issue of ammonia slip was raised, specifically whether it might affect the accurate measurement of methane and/or other emissions. Post workshop research indicates this should not interfere with the measurement[63].

5.6 Further considerations of the driving cycle

Post-workshop conversations with testing organisations focused on better understanding “current best practice for making accurate CO_2 and vehicle emissions measurements”. These revealed that the key aspects relevant to this study are:

- A minimum of three runs should occur for each driving cycle, in each vehicle test condition (e.g. diesel only or dual fuel mode), to obtain an indication of reproducibility and to identify outlying data, e.g. caused by a DPF regeneration.
- The actual time-speed profile of the run could vary from operator to operator. Generally it should be tailored to specific usage patterns.
- To undertake testing in a pattern A B A, where A and B represent the vehicle in different configurations, e.g. operating on diesel only, dual fuel, and then back to diesel only. This helps identify for longer term trends in the emissions. Testing, for example, diesel only one day and dual fuel on a different day can lead to errors if the emissions are changing with time.

The workshop encouraged the specification and use for track testing of a standard, previously developed driving cycle. Regulation 582/2011 also gives an overall speed envelope for this cycle, and there is a desire from some stakeholders that the cycle recommended is consistent with the PEMS testing requirement of 582/2011 such that the results from vehicle tests that are in accordance with the EC regulation are also in accordance with this test protocol.

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[63] The interference of FID THC signals caused by ammonia was checked. It is reported that TUV/MCERTS Certification tests results for a typical FID both CO and NH_3 are reported as not producing a response during interference checks.

Another major post workshop focus was on the need to collect good quality CO_2 emissions data for the comparator vehicle. The principal aim of the project is to provide a test protocol to quantify the **change in greenhouse gas emissions** of the methane fuelled vehicles relative to comparator liquid fossil fuelled vehicles. This involves measuring changes in CO_2 emissions relative to the comparator vehicle, which is discussed in Section 3.5. It has become apparent that pre-existing data, e.g. from the Low Carbon Truck Demonstration Trial may not be sufficiently robust in the context of meeting the project's aim. It was therefore decided that the test protocol should not only measure methane and CO_2 emissions from the methane fuelled vehicle, but also include, wherever practical, the measurement of principally CO_2 emissions from the comparator vehicle. This involves testing dual fuel vehicles in both their methane/diesel and diesel only fuelling configurations.

6 Final Recommendations

From drawing together the three tasks that comprise this study, the initial literature survey, the vehicle testing, the stakeholder workshop and post-workshop discussions with DfT and their advisors, this section provides:

- Details of the Recommended Test Protocol;
- Recommendations for further testing appropriate to improve the evidence base on methane emissions from gas fuelled HGVs; and
- Some thoughts on the vehicle technologies currently in use and under development including the extension of this test protocol to other methane fuelled heavy duty vehicles.

6.1 Details of the recommended test protocol

The vehicle:

The test is applicable to both dedicated methane vehicles and dual fuel diesel/methane vehicles. It is recommended that whole vehicles should normally be tested with 50% to 60% payload weighting, as specified by EU legislation for checking the in-use compliance of heavy duty vehicles with air quality emissions limits (regulation 582/2011/EC). However, specifying a strict 50-60% payload range could impose an unnecessary constraint, e.g. on assessing how methane slip varies with payload, so it should be open to the test commissioner to define the appropriate payload.

Fuel:

A sample of the methane fuel used should be taken and analysed because fuel quality is a variable that has been shown to affect methane emissions, and currently there are a range of methane fuel qualities available. This requirement may be relaxed if it is found that either there is little variability in fuel quality, or little correlation with the amounts of methane and other emissions expelled from HGVs during a typical drive cycle.

It is presumed that the diesel used in dual-fuelled vehicle will conform to EN 590 and the methane and ethane content of gaseous fuels should be known.

Track or road testing:

To meet the protocol’s objectives, track testing is advocated.

Whilst road testing is potentially a valid alternative, advocated in the EC Directives for checking in use emissions, such testing has limited accuracy in determining changes in CO_2 emissions relative to the comparator vehicle. Therefore we consider that it is not appropriate for this test protocol.

Driving cycle:

The test protocol should reflect the real operation of the type of vehicles that will be tested. It is also vital that the driving cycles have similar average speeds and kinetic intensities to those used for the comparator vehicle. For a dual fuel vehicle this will most likely involve driving time-speed profiles that emulate urban, rural and motorway driving conditions with the vehicle in both dual fuel and diesel only modes. For a dedicated methane vehicle the choice of driving cycles needs to be directly comparable with the data available, or the testing undertaken, of the comparator vehicle.

Test procedure

The details of a suitable test procedure to be followed for track testing has been written by Millbrook Proving Ground, building on their considerable experience of both PEMS heavy-duty vehicle testing and ensuring it is complementary to chassis dynamometer testing. This is given in Appendix 5. For the measurement of the changes in CO_2 more robust data is produced if fuel consumption can also be monitored. Options for achieving this include:

1. Fitting a diesel fuel flow meter, as was done in this study, so that the diesel consumption of the vehicle can be measured in diesel only and dual fuel mode for the vehicle as it is tested; and
2. Monitoring the diesel fuel usage from the vehicle’s CAN bus, so that the diesel consumption of the vehicle can be measured in diesel only and dual fuel mode for the vehicle as it is tested.

The two options are listed in potential order of accuracy, but this does have associated restrictions and cost implications. For example not all organisations able to offer PEMS measurements would be able to also fit a diesel fuel flow meter.

The test schedule recommended has been generated with the assumption that the battery life of the PEMs kit is around two hours. The test schedule recommended is:

- Zero and span the PEMS analysers;
- 20 minute vehicle warm up (that is consistent between vehicles and tests);
- Three 25 – 30 minute driving cycles; and
- Re-zero and span the PEMS analysers.

This schedule should be repeated three times in a day, generating data from nine driving cycles. The three 25 – 30 minute driving cycles may comprise triplicates of the same cycle, with the urban, rural and motorway cycles driven in the three separate periods of testing, or comprise the urban, rural and motorway cycles driven sequentially in each period of testing, with the replicates being driven in the three separate periods of testing.

For dual fuel vehicles the test schedule should be rerun on two consecutive days that have comparable weather conditions, in the dual fuel and diesel only fuelling modes.

The analysers used

The vehicle's emissions are to be analysed using Portable Emissions Monitoring Systems (PEMS) equipment (using equipment consistent with the PEMS specification in Annex II of Regulation 582/2011/EC). Methane should be measured (indirectly) using a flame ionisation detector (FID) which actually measures total hydrocarbon emissions, but these can be used as a suitable proxy for methane in methane fuelled vehicles. These requirements do not exclude any of the three main current types of PEMS systems available, and keep the measuring equipment consistent with the type approval regulations.

It is noted that this is a pragmatic solution based on currently available PEMS equipment. However, methane sensors are becoming available, and potentially more affordable. In the future it may be that a methane sensor becomes increasingly practical. Therefore methane sensing should not be excluded from future use, but should not currently be a requirement of the test protocol.

The subsequent data analysis

The data analysis involves calculating the methane, CO_2 and other emissions for the vehicle under test when using methane fuel, and comparing these with the emissions from a diesel-only comparator vehicle, and assuming its methane emissions are negligible. This involves relatively standard data analysis, similar to that experienced in the PEMS testing of vehicles.

If a diesel fuel meter is used its data should be analysed to give overall, and drive cycle segment, fuel consumption data for the vehicle in its diesel only and dual fuel modes.

From the above data (the emissions in the dual fuel and diesel only mode, and possibly from diesel fuel usage measurements too) the change in CO_2 emissions, and its margin of error, can be calculated, both in overall terms and expressed as g/km. Similarly, THC and other emissions can also be calculated from the dual fuel and diesel only modes. The worse-case scenario, with regard to GHG emissions, is to assume all THC emissions are from methane. This has been assumed to have a global warming potential of 28, relative to CO_2 on a mass for mass basis[64]. Therefore the net change in GHG emissions for the vehicle tested, driven over the specified driving cycle in its dual fuel mode, relative to running on diesel only, is:

28 x methane emissions – change in CO_2 emissions.

For modelling the overall change in GHG emissions the weightings for the component driving cycles need to be established. For example, for an articulated truck driving predominantly on trunk roads and motorways it might be appropriate to use: 20% urban cycle + 20% rural cycle + 60% motorway cycle.

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[64] Global warming potentials are expressed in terms of being relative to an equivalent mass of CO_2, over a fixed period of time. The 100 year GWP for methane is given as 28 in the 5th IPCC Assessment Report (See Box 3.2 in reference http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf . However, this was revised upwards relative to the 100 year GWP for methane of 25 as given in the 4th IPCC Assessment Report and the current value adopted by the UNFCCC for national emission reporting. In this study we use 28, the more recent figure.

Whereas for an urban delivery truck it might be appropriate to use: 60% urban cycle + 20% rural cycle + 20% motorway cycle. **Simply applying equal weight to all drive cycle components may not give an accurate reflection of the vehicle's performance during normal driving patterns.**

For dedicated methane vehicles the test protocol suggested does not include taking measurements from a (diesel) comparator vehicle. The contribution to the vehicle's GHG emissions from methane emissions can be relatively easily assessed from the emissions data collected from the methane fuelled vehicle. However, its overall GHG emissions relative to a comparator vehicle would require further information or (if sufficiently robust information is not available) further testing of such a vehicle.

Other aspects of the test protocol

These should be consistent with the PEMS specification in Annex II of Regulation 582/2011/EC. Specifically with regard to:

- Ambient conditions, pressure > 82.5 kPa; temperature > -7 C;
- Engine coolant temperature; and
- Exhaust temperatures.

An important additional aspect that is currently not specified is the definition of a "standard" trailer for the testing of articulated tractor units. Initial consultations have indicated this should be a curtain trailer type of standard height.

Consideration of the output

A key aim of this project is to measure the overall GHG emissions from methane powered vehicles (in terms of CO_2e and covering, as a minimum, tailpipe CO_2 and THC[65]).

In the protocol developed, the change in overall GHG emissions can be expressed as:

Δ GHG emissions = Δ CO_2 emissions + Δ Methane emissions * GWP (methane, i.e. 28)

Where Δ Species = Concentration of species from the methane fuelled HDV

less the concentration of species from diesel only fuelled comparator HDV.

Using data from the first annual report to the DfT on the Low Carbon Truck Trial it was found that, averaged over the fleet, the CO_2 emissions savings were 72 g/km (9%). A methane slip of **2.6 g/km** would be equivalent a further 72.8 g CO_2e/km (100 year GWP for methane taken as 28) and would just counteract the direct CO_2 savings generated.

6.2 Recommendations for further testing appropriate to improve the evidence base on methane emissions from gas fuelled HGVs

The stakeholder workshop identified three different dimensions regarding vehicles that used methane fuels. These covered the dedicated methane and dual fuelled vehicles, the existing and future fleet, and OEM and after-market vehicle conversions. Some characteristics of the current and anticipated future fleet sizes are given in Table 6-1. Allied to this is an assessment as to their methane emissions.

The recommendations regarding further testing are:

- Restricted to categories where vehicles actually exist, e.g. current OEM dedicated and aftermarket dual fuel conversions;
- In the future it is anticipated this will extend to include OEM dual fuel vehicles;
- To focus on vehicles likely to be used commonly over the coming years, rather than the historic fleet. The latter are present in relatively modest numbers, a number of studies regarding their emissions have been made, and investing in finding the emissions from more of these vehicles in further detail probably has modest benefit.

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[65] N_2O, another important greenhouse gas, has also been considered but its measurement is considered to be non-essential at this time.

- To focus on the aftermarket dual fuel vehicle conversions because, unlike the OEM manufactured vehicles, these are unlikely to have been formally type approved and their GHG emissions are currently more uncertain. However OEM manufactured vehicles should still be tested in the same way as other types to build an evidence base on overall GHG savings.

Table 6-1 Summary of methane vehicles and assessment as to their methane emissions

Type of vehicle	Methane vehicle producer	
Existing fleet		
Dedicated methane	OEM	Relatively few vehicles Performance generally good
Dedicated methane	After-market conversion	Very rare – not worth considering
Dual fuel	OEM	Very rare for trucks – not worth considering
Dual fuel	After-market conversion	Moderate number, encouraged by Low Carbon Truck trial, and is the dominant type of vehicle within that trial. Produced by several manufactures. Currently not Type Approved, although regulatory framework does exist. Methane emissions performance found to be very variable depending on conversion strategy, vehicle durability and other factors.
New (Euro VI) fleet		
Dedicated methane	OEM	Increasing number of vehicles Type approved by the OEM Methane emissions performance anticipated to be good
Dedicated methane	After-market conversion	Very rare – not worth considering
Dual fuel	OEM	Increasing but relatively small number of vehicles Type approved by the OEM Methane emissions performance anticipated to be good
Dual fuel	After-market conversion	Growing market with several producers – could well be the dominant source of vehicles in the fleet. Currently not Type Approved, although regulatory framework does exist. Methane emissions performance anticipated to be variable depending on conversion strategy, vehicle durability and other factors.

The different aftermarket dual fuel vehicle conversion companies have different strategies. At this stage, in the context of a rapidly developing technology, there is no clear way of accurately assessing the levels of methane emissions because there are too many interacting parameters, such as the varying age and performance of methane catalysts. It is recommended that further testing of after-market produced dual fuel vehicles takes into account the following factors:

- Test vehicles from each of the companies who produce after-market dual fuel vehicles;
- Endeavour to engage with the companies who produce after-market dual fuel vehicles to better understand when technology changes are likely to occur, and the general ethos of the companies (e.g. in terms of research, their relationship with OEMs whose vehicles are being converted, etc.);
- Also, it is strongly recommended to engage with OEMs who produce dual fuel vehicles to better understand what factors they have found influence particularly durability;
- A corollary to this would be to build up a database of the different companies who produce after-market dual fuel vehicles, the base vehicles they convert, and the numbers converted as a function of time; and
- Remain aware of the rapid pace at which innovation is occurring, particularly in the context of the base vehicles' technology changing with the introduction of Euro VI emissions standards. This means results obtained cannot be simply extrapolated to the previous and later generations of converted vehicles.

The above recommendations give an outline of further testing that could occur. EC Directives and Regulations covering Conformity of Production have relatively complex sections describing how the number of tests depends on the variability of the results of testing, and the average value in terms of the desired outcome. Appendix 1 of UN ECE Regulation 49 details the procedure to be used for production conformity testing when the standard deviation is satisfactory. The minimum number of vehicles to be tested is three. For this project, where the overall target is to have no increase in GHG emissions from a fossil methane fuelled vehicle, some possible scenarios, and responses might be:

- **Scenario 1** – A Dual fuel vehicle has low methane emissions and a clear GHG reduction with fossil methane. Understanding the standard deviation of test results for several nominally identical vehicles (e.g. 3 according to UN/ECE Regulation 49), is necessary to confirm this is not an outlying result. If the result applies to two, or better to three vehicles then suggest evidence base is complete for this vehicle at this date.

- **Scenario 2** – A Dual fuel vehicle has a very high methane emissions and a clear GHG increase with fossil methane. As for scenario 1, it is important to understand whether or not this is an outlying result, i.e. at least two vehicles should be tested. Assuming the results are similar, then although this suggests the evidence base is complete for this vehicle at this date, the follow up question is what further actions are appropriate.

- **Scenario 3** – A Dual fuel vehicle has modest methane emissions and the change in GHG increase with fossil methane. Again, it is important to understand the standard deviation of testing several nominally identical vehicles. However, unlike the EC regulations where there is a clear emissions requirement, for the building up of an evidence base it would not be appropriate to extend the number of vehicles tested.

Ultimately, the future testing appropriate to building up the database of methane emission rates involves identifying the sensitive population of vehicles, undertaking an audit as to the size and key parameters involved in the fleet, and prioritising the available budget and the range of different parameter values. In addition, the future testing that can be undertaken will also depend on vehicle operators, suppliers and/or technology developers making vehicles available. This too will involve prioritising the opportunities and making judgements.

6.3 Considerations of the potential extended use of the test protocol

The test protocol developed and described in this report can be extended to other methane fuelled heavy-duty vehicles.

The principal variations are:

- **The driving cycle:** For buses or small delivery trucks the test cycle should be reviewed. For example, while for long haul trucks normal vehicle usage involves long distances travelled on motorways and trunk roads, for a small delivery truck a more appropriate cycle might be the whole WHVC, whereas for a city bus, which does not travel on motorways etc. it might be restricted to urban and rural driving only.

- **The selection of comparator vehicle CO_2 emissions:** For dual fuel vehicles testing in diesel only and methane/diesel modes is recommended but for dedicated methane vehicles there is the challenge of identifying relevant comparative diesel only vehicles for which appropriate emissions data are available. Alternatively, it involves testing, using the recommended procedure, both the dedicated methane vehicle and the selected comparator vehicle.

7 Glossary

CBM	Compressed Bio-methane
CEAS	Cavity Enhanced Absorption Spectroscopy
CeO_2	Ceria
CH4	Methane
CI	Compression Injection
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampling
DDF	Diesel Duty Fuel
DfT	Department for Transport
DPFs	Diesel Particulate Filter
DVSA	Driver and Vehicle Standards Agency
ECE	Economic Commission for Europe (often referred to as UN ECE)
ECU	Electronic control unit
EEV	Enhanced Environmentally friendly Vehicles
EGR	Exhaust Gas Recirculation
ELR	European Load Response
EPA	Environmental Protection Agency
ESC	European Stationary Cycle
ETC	European Transient Cycle
FID	Flame ionisation detector
FIGE	FIGE Institute (Germany)
FTIR	Fourier Transform Infrared Spectroscopy
GER	Gas Energy Ratio
GHG	Greenhouse gas
G/km	Grams per kilometre
G/kWh	Grams per kilowatt-hour
GPS	Global Positioning System
GSR	Gas Substitution Ratio
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HC	Hydrocarbon

HDDF	Heavy Duty Dual Fuel
HDV	Heavy Duty Vehicle
HGV	Heavy Goods Vehicle
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel for Climate Change
LBM	Liquid Bio-methane
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
MOT	Ministry of Transport test
NDIR	Non-Dispersive Infrared Absorption
NH3	Ammonia
NO	Nitric Oxide
NOx	Nitrogen Oxide
NMHC	Non-Methane Hydrocarbons
OEM	Original Equipment Manufacturer
Pd	Palladium
PEMS	Portable Emissions measurement System
PI	Positive-Ignition
PM	Particulate Matter
PN	Particle number
Rh	Rhodium
SCR	Selective Catalytic Reduction
SI	Spark Ignition
THC	Total Hydrocarbon
TWC	Three-way catalyst
VOC	Volatile Organic Compounds
VTEC	Variable Temperature Emissions Chamber (name given to Millbrook’s heavy-duty emissions dynamometer facility)
WHTC	World Harmonised Test Cycle
WHVC	World Harmonised Vehicle Cycle

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Appendices

Appendix 1

European HDV Manufacturers of Methane Vehicles

A summary of the seven principal heavy duty vehicle engine manufacturers in Europe, and what methane vehicles they offer is provided in Table 1-1 of the main report. The information in the table was obtained from a wide range of sources, including talking to some engine manufacturers directly, and from information publically available on the internet. A list of these is given below. This is not intended to be exhaustive, but identifies the sources of information used to generate the table.

Details of Internet European HDV manufacturers of methane vehicles

Manufacturer	Internet sources of information
Iveco	Discussion directly with Iveco
DAF (part of PACCAR)	DAF - http://www.daf.eu/UK/Trucks/Documents/Road-Transport-and-the-Environment.pdf
Daimler (Mercedes-Benz)	Discussion directly with Daimler
Volvo (also includes Renault Trucks)	Volvo DF vehicle: http://www.cleanairpower.com/Dual-Fuel%20Technology.pdf Volvo LNG DF vehicle: http://lngbc.eu/node/31 Volvo Dedicated methane vehicle: http://www.ngvglobal.com/volvo-trucks-adds-methane-powered-fe-model-0823
Scania	Scania: http://www.scania.co.uk/about-scania/media/press-releases/2014/06/scania-introduces-the-first-uk-dedicated-gas-powered-euro-6-truck.aspx Scania: http://www.diva-portal.org/smash/get/diva2:533308/FULLTEXT01.pdf
MAN	http://www.manbusandcoach.co.uk/news/eco-city/ http://www.hit.ac.il/mc/ebngbt/presentations/Robert%20Staimer,%20MAN.pdf MAN Ship DF - http://www.man-bluefire.com/tl_files/man_bluefire_files/pdf/Brochure%20engine%2035-44DF.pdf
Cummins	http://www.cummins.com/global-impact/sustainability/environment/products/natural-gas-engines
Clean Air Power	Sainsbury “Running on Rubbish” vehicles http://www.ngvglobal.com/sainsburys-adds-more-dual-fuel-truck-to-uk-fleet-0226

List of vehicles which use CNG, both dedicated and dual fuel http://www.cngas.co.uk/cngvehicles.php

Gas vehicle hub: http://www.gasvehiclehub.org/gas-vehicle-availability/retro-fit-systems

Appendix 2

Diesel HDV Exhaust Air Pollutant Data

Methane (CH_4) emissions reduction factors (%) for heavy-duty diesel trucks. Reductions are relative to Euro I.

(This is part of Table 3-73 of the EMEP/EEA air pollutant emission inventory guidebook 2013, available from http://www.eea.europa.eu/publications/emep-eea-guidebook-2013).

Vehicle technology class	**CH_4 Emission reduction factors (%)**		
	Urban	Rural	Highway
Euro II	36	13	7
Euro III	44	7	9
Euro IV	97	93	94
Euro V and later	97	93	94

Composition of NMVOC in exhaust emissions for heavy-duty diesel trucks.

(This is part of Tables 3-112a and 3-112b of the EMEP/EEA air pollutant emission inventory guidebook 2013, available from http://www.eea.europa.eu/publications/emep-eea-guidebook-2013).

Group	**Species**	**NMVOC Fraction (% wt)**	
		HDV	Gasoline 4 stroke (Euro I & on)
Alkanes	Ethane – nonane	2.24	26.4
	Decane	1.79	0.19
	Alkanes C10 – C12		1.76
	Alkanes C > 13	27.5	1.45
Cycloalkanes	All	1.16	1.14
Alkenes	Ethylene	7.01	7.30
	Propylene	1.32	3.82
	Iso-butene	1.70	2.22
	1,3 butadiene	3.30	0.91
	Other alkenes		2.97
Alkynes	Acetylene	1.05	2.81
	Other alkynes		0.29
Aldehydes	Formaldehyde	8.40	1.70
	Acetaldehyde	4.57	0.75
	Acrolein	1.77	0.19
	Benzaldehyde	1.37	0.22

	Crotonaldehyde	1.48	0.04
Aldehydes (continued)	Methacrolein	0.86	0.05
	Butyraldehyde	0.88	0.05
	isobutanaldehyde	0.59	
	propionaldehyde	1.25	0.05
	hexanal	1.42	
	i-valeraldehyde	0.09	
	valeraldehyde	0.40	0.01
	o-tolualdehyde	0.80	0.07
	m-tolualdehyde	0.59	0.13
	m-tolualdehyde		0.06
Ketones	All		0.66
Aromatics	toluene	0.01	10.98
	ethyl-benzene		1.89
	m,p-xylene	0.98	5.43
	o-xylene	0.40	2.26
	1,2,3 trimethylbenzene	0.30	0.86
	1,2,4 trimethylbenzene	0.86	4.21
	1,3,5 trimethylbenzene	0.45	1.42
	styrene	0.56	1.01
	benzene	0.07	5.61
	C9	1.17	4.21
	C10		3.07
	C>13	20.37	3.46
TOTALS	**(all NMVOC species)**	**96.71**	**99.65**

Appendix 3

Details regarding possible drive cycles

Testing strategies for HDVs: Regulatory testing

Heavy duty diesel emission standards were first adopted in July 1988[30]. Since this time, type approval has been performed on new engine designs before they are incorporated into heavy-duty vehicles. Consequently limit values have been expressed in units of grams per kilowatt-hour (g/kWh) rather than grams per kilometre (g/km) (the latter is used for measuring and regulating emissions from light duty vehicles). All current and historical engine tests are pass/fail, dependent on whether particular emissions over the entire test exceed specified limits (see Table 1-3). The engines are tested separately before they are built into vehicles. This is principally due to the high diversity of available vehicle configurations compared to the number of annual registrations and compared to the much smaller number of engine models that are used. Testing the engine directly promotes investment into advanced engine technologies, which otherwise may take many additional years to reach the market.

A summary of the driving cycles considered in this appendix was given in Section 3.7 of the main report.

Engine dynamometer tests

ECE R-49

Euro I and II used the R-49 diesel engine test cycle[66] for type approval testing, performed on an engine dynamometer. The whole cycle takes emission readings from ten distinct engine speed-load points, interspersed with three measurements at idle; hence it is often referred to as the 13-mode test. As a steady-state test this suffered from significant differences between type approval and real-world emissions, principally due to the different optimisations in various parts of the engine map which manufacturers were able to exploit with the latest injection and control technologies. NO_x emission disparity was especially problematic. For these reasons, the ECE R-49 procedures are not considered in this study.

European Stationary Cycle

In an effort to offset the increasing 'cycle beating' techniques utilised by engine manufacturers and as a result of the Auto-Oil Programme[67], the ECE R-49 test was replaced in 2000 by two cycles: the European Stationary Cycle (ESC) and the European Transient Cycle (ETC). These were introduced in line with the Euro III emission standards[68], and included the first formal consideration for natural gas vehicles. One of the major improvements of the new tests was the real-world measurements on which they were based, validating their suitability for evaluation in this study. The tests are both performed on engine dynamometers - the FIGE[69] cycle on which the ETC is based did have a chassis dynamometer test counterpart. However, this was not adopted for type approval purposes. For the Euro regulations, the cycles were supplemented by the European Load Response (ELR) test which measured smoke opacity and provides a degree of connection to the in-service roadworthiness emissions "Free Acceleration Smoke" test. The choice of test was determined by the fuel and after-treatment systems of the HDV in question, and was modified in line with after-treatment technology progression with the introduction of Euro IV[70] (see Table A3-1).

The ESC procedure concerns the testing of heavy duty compression ignition engines over a sequence of 13 steady-state modes with defined engine speeds (±50 rpm), loads and durations. Ten of the 13 modes were considered to be 'high loading', a benefit of the ESC. Excluding idle, the three engine speeds used are set as a function of the declared maximum net power of the engine, introducing a variability which better reflects real-world differences between engines. The test measures carbon monoxide (CO), hydrocarbon content (HC) and nitrous oxides (NOx) using a weighted-average of the emissions during each mode (when the engine speed and load are stable). Particulate matter (PM) emissions are measured over the duration of the test.

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[66] Introduced by UN ECE Regulation 49 in 1982.

[67] http://ec.europa.eu/environment/archives/autooil/index.htm.

[68] Introduced by Directive 1999/96/EC, amending Directive 88/77/EEC.

[69] FIGE Institute, Aachen University.

[70] Directive 2005/55/EC.

Table A3-1: Choice of test for available engine types

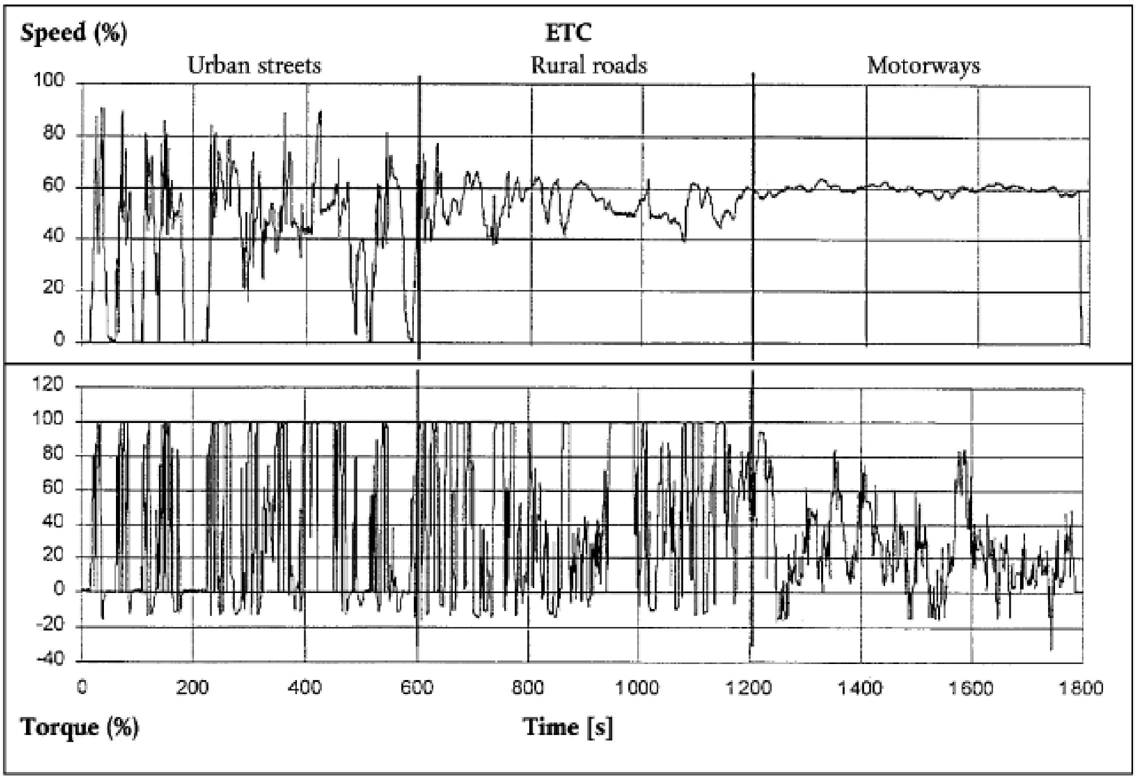
Engine Type	Specifics	Applicable Procedures		
		Euro III	Euro IV - V	Euro VI
Compressive ignition	Conventional diesel	ESC and ELR	ESC, ELR and ETC	WHSC and WHTC
	'Advanced after-treatment' diesel (NOx after-treatment, diesel particulate filters (DPFs))	ESC, ELR and ETC	ESC, ELR and ETC	WHSC and WHTC
	Enhanced environmentally-friendly vehicles (EEVs)	ESC, ELR and ETC	ESC, ELR and ETC	WHSC and WHTC
Positive ignition	Natural gas, LPG	ETC	ETC	WHTC

Source: European Commission, 2005

European Transient Cycle

The ETC cycle introduced a further degree of realism to the HDV testing procedure. Urban, rural and motorway driving conditions were emulated by splitting the test into three, ten-minute sections. The urban section comprises frequent start-stop driving and has a maximum speed of 50km/h; the rural driving section has an average speed of roughly 70 km/h with harsh accelerations; and the final motorway section tests at a relatively steady, higher average speed of roughly 90 km/h. This is graphically represented in Figure A3-1. The ETC was the first test cycle to include special provisions for natural gas vehicles, which had methane emission limits imposed by Euro III and tightened in 2005 by Euro IV.

Figure A3-1: The European Transient Cycle Dynamometer Schedule



Source: Directive 2005/55/EC

In steady-state operation, systematic optimisation of emissions, engine response and fuel consumption is possible which can be exploited by manufacturers to artificially increase the cleanliness of an engine as it appears during testing, known as 'gaming'[71]. The inclusion of a *transient* cycle in the type approval process partially mitigates any gaming and can reveal more about a vehicle's real-world performance - the engine map is not sampled at discrete points of stable operation but continuously through all points of operation under representative scenarios. It is more difficult to hide poor emission performance regimes as there exists an inherent trade-off between the aforementioned characteristics under transient conditions. Transient conditions occur between steady-state operations and have profound effects on emissions – contributing many times more emissions than steady state operation over a drive cycle (Rakopoulos, Giakoumis, Hountalas, & Rakopoulos, 2004) - especially for diesel engines. For example, at the time Euro III was introduced, when increased power was demanded from a diesel engine the air/fuel mixture was made temporarily rich and was insufficiently mixed, producing unfavourable oxidation conditions and hence increased particulate matter until the air to fuel ratio returned to steady-state (Hagena, Filipi, & Assanis, 2006). NO_x emissions during accelerations were similarly affected; a delay between increased fuelling and the response of the air-charging system, coupled with momentarily increased peak injection pressures (permitted by the powertrain control module) raised NO_x levels in the combustion residue (Obländer, Kollmann, Krämer, & and Kutschera, 1989). Both of the above are emphasised when EGR is present, as commonly used in HGV engines (however, conversely EGR significantly reduces the formation of NOx in steady state operation). Naturally, frequent and dynamic transient events will result in large impacts on emissions which is particularly relevant for applications of intermittent use, such as waste collection trucks, buses and other vehicles which have been put forward for their potential for conversion to CNG. This also applies to hybrid vehicles; transient cycles better reflect their real-world emissions as although the electrical systems allow refined control of the powertrain system, their optimisation for fuel consumption has been shown to lead to frequent and harsh load increases on the engine (heavy loading for best efficiency) (Filipi, Fathy, Hagena, & Knafl, 2006) which, if not controlled effectively, can result in emission spikes.

The extent of the increase in emissions during transient events has been shown to vary considerably by cycle (Samulski & Jackson, 1998) (Clark, Gautam, Rapp, & Lyons, 1999), so it is important that any cycle recommended by this study reflects real-world driving as best it can if accurate results are to be achieved in testing. This will be discussed further in Chapter 7, in the context of the reliability of testing.

Although the ESC and ETC tests were innovative developments in the history of engine testing, their success was limited by their divergence from real-world driving. Both had a high average load, resulting in concentrated manufacturer efforts to reduce emissions under this condition but neglecting low-load and low-speed emissions which are typical of actual urban usage. The ETC allowed for excess NOx emissions in this regime, which in real-world cases could exceed those of Euro III vehicles (Jun & Wagner, 2013). One of the principal mechanisms (Lowell & Kamakaté, 2012) by which this occurred was through the selective catalytic reduction (SCR) systems employed by diesel engine manufacturers to convert NOx to N_2O – this relies on a high exhaust temperature for efficient conversion which is characteristic of the ESC and ETC but not of urban driving. Figure A3-2 displays this phenomenon for an SCR-equipped Euro IV truck, tested using PEMS. In addition, manufacturers are able to pre-condition the engine under the procedures, and so most opt to start when the engine is hot and exhaust temperatures correspondingly high. The procedures do not include a cold start test which would have partially mitigated this oversight.

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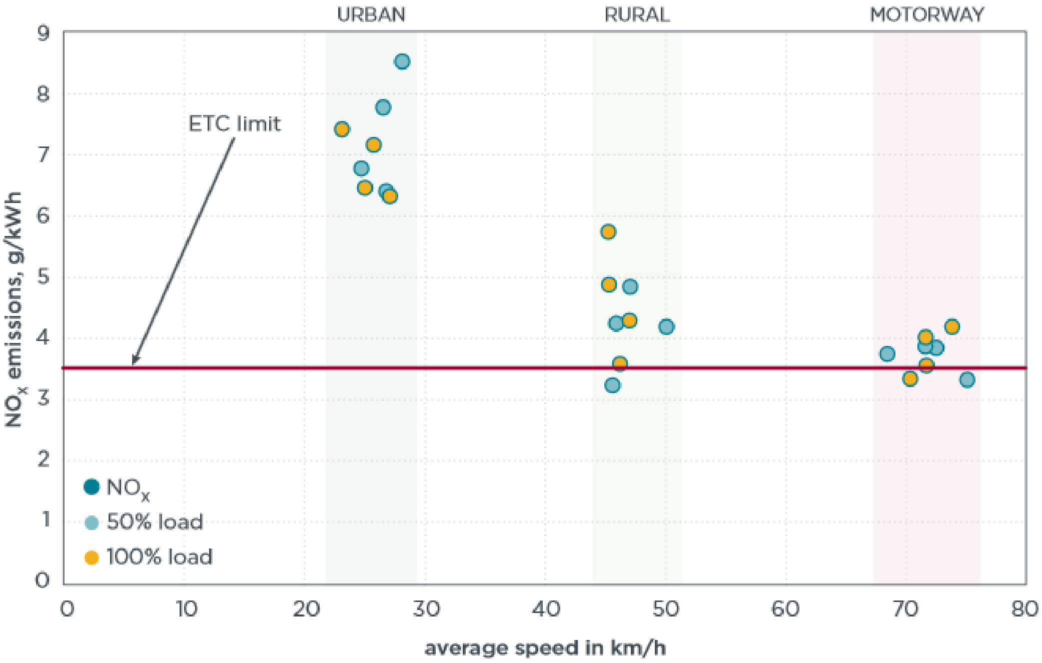
[71] This issue was formally addressed in Directive 2001/27/EC which amended Annex I of the earlier Directive 88/77/EEC. In this, a definition and prohibition (section 6.1.2.1) is given of an "irrational emission control strategy" which could reduce the effectiveness of any emission controls outside of the type approval environment.

Figure A3-2: NOx emissions of an 18t SCR-equipped Euro IV truck performed on German roads using PEMS

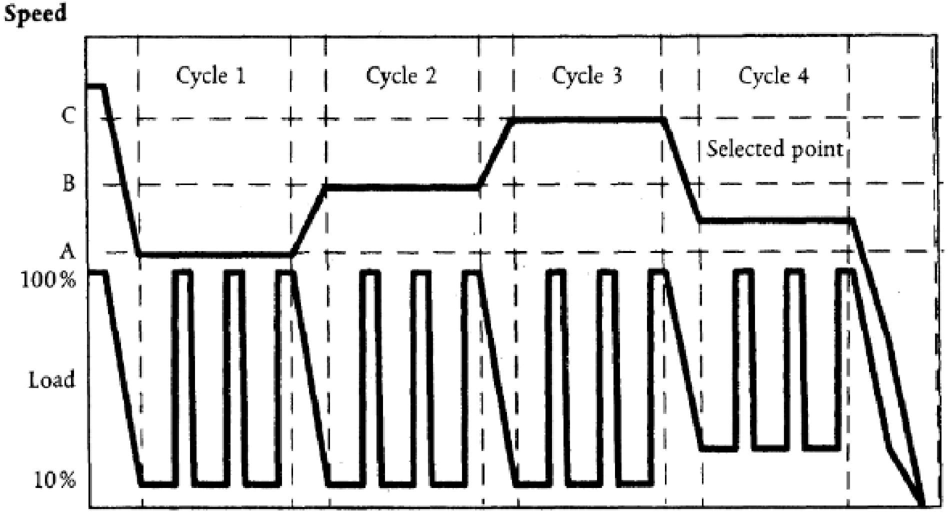


Source: **(Jun & Wagner, 2013)**

European Load Response Test (ELR)

The ELR was also imposed at Euro III through Directive 1999/96/EC to measure smoke opacity from heavy duty diesel engines. It is composed of four cycles run at three load steps and three speeds (see Figure A3-3), which are equivalent to the speeds defined for the ESC (a function of the declared maximum net power of the engine). The smoke is measured in m^{-1} and the limit value was reduced (from 0.8 m^{-1} for Euro III) to 0.5 m^{-1} for the Euro IV amendments in 2005. Although the ELR plays an important role in the testing of Europe's primarily diesel HDV fleet, it is less important for methane-fuelled vehicles which have relatively low particulate emissions. It is notable that with the introduction of the World Harmonised cycles as part of Euro VI testing, the ELR is no longer a test requirement.

Figure A3-3 – The ELR test sequence



Source: **(UN ECE, 2014)**

Worldwide Harmonized Steady-state Cycle (WHSC)

The Worldwide Harmonized Steady-state and Transient (WHSC and WHTC) test cycles took effect for type approvals from 2013 as part of the Euro VI heavy duty emissions standard. The cycles are outputs of the UN ECE Group on Pollution and Energy's global technical regulation #4, which was dedicated to specifying a worldwide harmonised heavy-duty certification procedure. They were developed to address the shortcomings of the ESC and ETC and in particular to force manufacturers to employ NO_x reduction strategies which function across a realistic range of operating conditions (see (Chatterjee, Walker, & Blakeman, 2008) and Article I, 2011/595/EC).

The cycles are run on an engine dynamometer, including necessary exhaust after-treatment devices, but without the gearbox, drivetrain and any other auxiliaries. Both cycles include a defined procedure to condition the engine before the test starts - the WHSC is a hot start test. It is a 13-mode, linearly-ramped cycle which lasts for just over 30 minutes.

Worldwide Harmonized Transient Cycle (WHTC)

The WHTC was created to better reflect normal operation of heavy duty vehicles as compared to its ETC predecessor, as discussed above. Typical driving conditions in the EU, the USA, Australia and Japan are represented using a real-world data basis – the WHTC contains a greater proportion of low speed and low load time than the ETC. In order to further reduce the discrepancy between test-cycle and real world emissions, it runs from both cold[72] and hot starts and uses a weighted average[73] to amalgamate them. Subsequent work estimated the cold start WHTC reveals an increase in NO_x of 8-13% over the ETC (TNO, 2008). In contrast to preceding standards, under Euro VI, pre-conditioning regimes are specified and manufacturers are not able to define their own. Both hot and cold starts are performed, thus ensuring the time necessary to heat up the after-treatment system is accounted for within the emissions reading; a 10 minute 'hot soak' before the hot start test also identifies whether the after-treatment systems can cool to below the light-off temperature over short periods, capturing further real-world emissions.

The WHSC and WHTC use units of mg/kWh and not g/km as in previous tests. This is more than a cosmetic change and is significant from the view point of data rounding – as it is permissible to round down the measured emissions data, the impact of rounding errors is greatly reduced[74]. The WHTC also demands that the exhaust after-treatment system undergoes a regeneration process either permanently or at least once per WHTC hot-start test[75], adding a degree of realism. It is also worth noting that the emissions species regulated have increased to reflect the needs of society, the analysis instruments available, and the potential emissions from new vehicle technologies. These include particle number (PN) to augment the ever lower PM from vehicles fitted with diesel particulate traps, and ammonia (NH_3) to confirm the correct working of some NOx emissions reduction technologies.

Although the literature agrees that the world-harmonised cycles offer a great improvement over previous cycles, they inherently have some of the same generic constraints as their predecessors, in particular the potential poor relevance of engine testing to real-world vehicle emissions. The world-harmonised tests attempt to cover a very wide range of engines and applications which inevitably results in compromises. Concerns have been expressed that not all modes of operation, especially at low loads which the WHTC was introduced to combat, are reflected by the WHTC. (AVL, 2014) (TNO, 2014).

Summary

A summary of the emissions measured during over the different cycles is given in Table A3-2. The emission limits for Euro V and Euro VI standards are given in Table 1-3.

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[72] See UN ECE Regulation #49, Annex 4B.

[73] 16% cold start and 84% hot start emissions.

[74] For example, a measured level of 0.059g/km could be rounded to 0.05g/km when using a two decimal place system as preceded the Euro VI emission standards – the measured figure is 18% higher than reported. For a mg/km system, this rounding would have no impact at two decimal places.

[75] Regulation 582/2011.

Table A3-2 - Emissions measured by cycle

Testing Type	**Cycle**	**Emissions measured during different test cycles**								
		HC	NO_x	PM[a]	PN[b]	Smoke	CO	NMHC	CH_4[c]	NH_3
Static	ECE R-49	✓	✓	✓			✓	✓	✓	
	ESC + ELR	✓	✓	✓		✓	✓	✓	✓	
	WHSC	✓	✓	✓	✓		✓	✓	✓	✓
Transient	ETC	✓	✓	✓			✓	✓	✓	
	WHTC	✓	✓	✓	✓		✓	✓	✓	✓
PEMS	-	✓[b]	✓				✓	✓[d]	✓[d]	✓

Notes:

[a] Compression ignition only for Euro III-IV.

[b] Compression ignition only.

[c] Natural gas engines only for Euro III-V; natural gas and LPG only for Euro IV.

[d] Positive ignition engines only.

Source: UN ECE Regulation 49, Directive 1999/96/EC, Regulation 595/2009

Chassis dynamometer, computer simulations and vehicle testing

Although engine-testing spurs increased investment into advanced engine technologies, it does not promote efficiencies which could be economically attained elsewhere. Transmission and driveline friction improvements, for example, have been forecast to provide fuel savings of up to 10% (ACEEE, 2013) and their inclusion dramatically changes transient emission characteristics. Separation of the engine and vehicle removes any incentive to develop integrated strategies such as aerodynamic improvements which facilitate technologies such as downsizing.

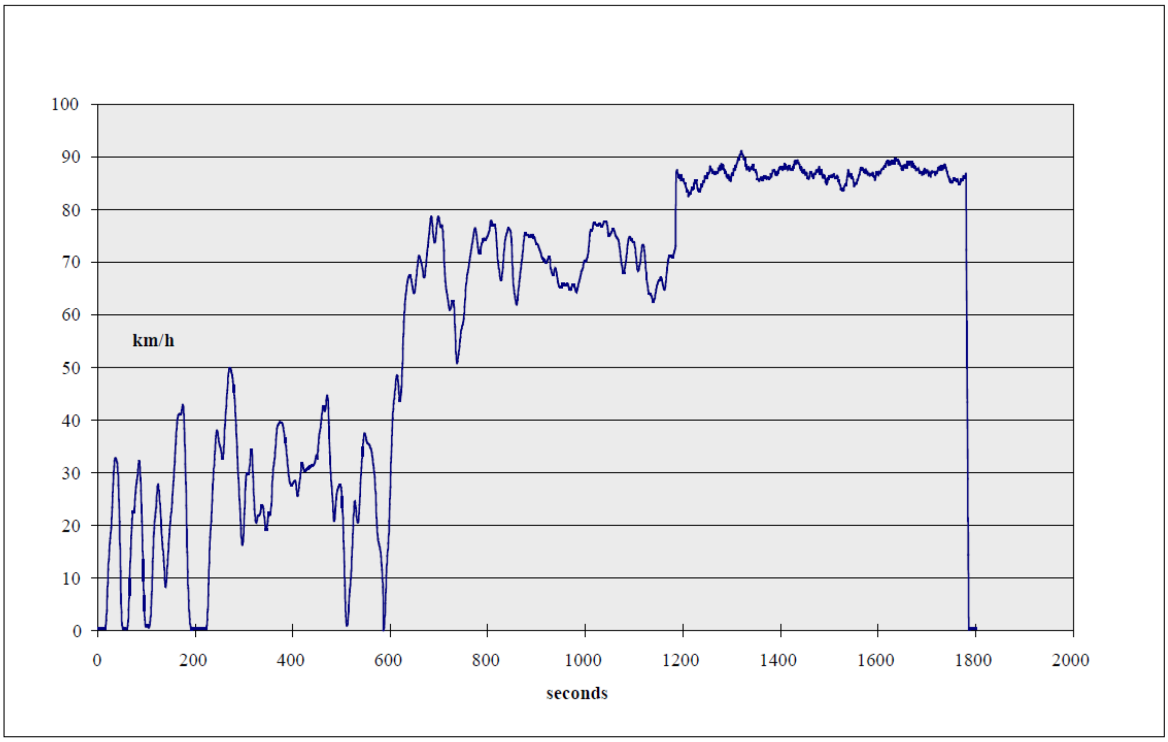
Predominantly, engine-only testing encourages optimisation for fixed engine cycles and not for application-specific real-world operation. Under engine cycles, a 12-tonne delivery van is treated equivalently to a 44-tonne articulated lorry. Engine efficiency is rating dependent and systematically favours the largest engines on the test bed. One consequence of this is that downsizing appears marginally detrimental on an engine cycle, whereas vehicle cycles reveal its benefits, caused by improvements to both engine characteristics and how each kWh of work delivered by the engine can achieve a little more, travelling a little further or carrying a higher load.

Vehicle testing generally creates pass/fail criteria on a per km basis, in contrast to engine testing which uses a brake-specific metric because no distance is involved. It is particularly advantageous for the purposes of this study because of its practicality – it involves testing of whole vehicles not sub-units. This is important for groups of vehicles where aftermarket modifications are prevalent. Chassis dynamometer testing is also of interest as it is considered to better represent the emissions from newer powertrains than engine dynamometers. (ICCT, 2012)

FIGE road cycle

The European Transient Cycle for engines (ETC) was developed by the FIGE Institute of Aachen University, Germany. It originated from studying the actual speed time profiles of many heavy duty vehicles. This information was then converted into an engine dynamometer test for regulatory testing because of its attractiveness in contrast to the challenges and poor practicality of using a chassis dynamometer. However, there remains the FIGE road cycle which can be used on a chassis dynamometer, although not for current regulatory processes. This is shown in Figure A3-4.

Figure A3-4: The FIGE test cycle – chassis dynamometer version of the ETC cycle



Source: AVL, 2010

This figure is also available in the DfT sponsored reference book of driving cycles for use in the measurement of road vehicle emissions (prepared by TRL in 2009.

The FIGE vehicle cycle can be sub-divided into three portions, each of 600 seconds duration, covering urban, rural and motorway driving. The principal characteristics of the whole cycle, and for each of these three components are shown in Table A3-3.

Table A3-3 Vehicle category-drive cycle combinations currently available for simulation runs in VECTO

Parameter	Whole FIGE cycle	Part 1 (urban)	Part 2 (rural)	Part 3 (motorway)
Duration	1,800 s	600 s	600 s	600 s
Total distance	29.49 km	3.87 km	11.56 km	14.06 km
Average speed	59.0 km/h	23.3 km/h	69.3 km/h	84.4 km/h
% of time cruising	47.72%	27.17%	37.00%	78.83%
% of time accelerating	29.00%	40.83%	36.33%	9.83%
% of time decelerating	23.28%	32.00%	26.67%	11.33%
% of time braking	8.61%	18.83%	5.50%	1.50%
% of time standing	0.00%	0.00%	0.00%	0.00%

Source: From DfT sponsored “Reference book of driving cycles for use in the measurement of road vehicle emissions” (prepared by TRL in 2009)

VECTO drive cycles

Although there currently are no heavy duty vehicle CO_2 regulations in the EU, the European Commission is now developing regulatory proposals in this area. As one of the central parts in the development of the CO_2 certification procedure, the EC launched the development of a “Vehicle Energy Consumption calculation Tool” (VECTO). VECTO aims to simulate CO_2 emissions and fuel consumption based on **vehicle** longitudinal dynamics using a driver model for backward simulation of target speed cycles. The required load to be delivered by the internal combustion engine is calculated based on the driving resistances, the power losses in the drivetrain system and the power consumption of the vehicle auxiliary units. However, at the time of writing the development of VECTO is “work in progress” and has yet to be validated. Notwithstanding, it drive cycles, in their current state of development, which involves having been agreed with ACEA, are worth noting.

Rather than drive cycles defining the speed-time profile to be followed, distances to be travelled and target speeds are specified on a metre by metre basis. This provides a more accurate simulation for HDVs where the same vehicle can have very different loads which lead to different speed-time profiles. For example, when pulling on to a trunk road the driver may wish to accelerate to the vehicle’s maximum speed as swiftly as possible, i.e. he applies full power. When fully laden the acceleration is slower than when lightly laden, the time taken to reach maximum speed will be longer, and the associated CO_2 emissions will be higher. VECTO simulates all of this over a “mission”, i.e. a specified distance to be travelled and target speeds at points along the route.

VECTO broadly uses four different types of heavy duty vehicles, rigid trucks, articulated trucks buses and coaches. Nine different missions/drive cycles have been specified:

- Truck urban delivery cycle;
- Truck regional delivery cycle;
- Truck long haul cycle;
- Truck construction cycle;
- Truck municipal utility cycle (e.g. for refuse trucks);
- Bus urban cycle;
- Bus heavy-urban cycle;
- Bus inter-urban cycle; and
- Coach cycle.

These have a variety of different distances travelled, varying from around 10 km for the municipal utility cycle to 275 km for the coach cycle. The characteristics of the four main truck cycles are summarised in Table A3-4.

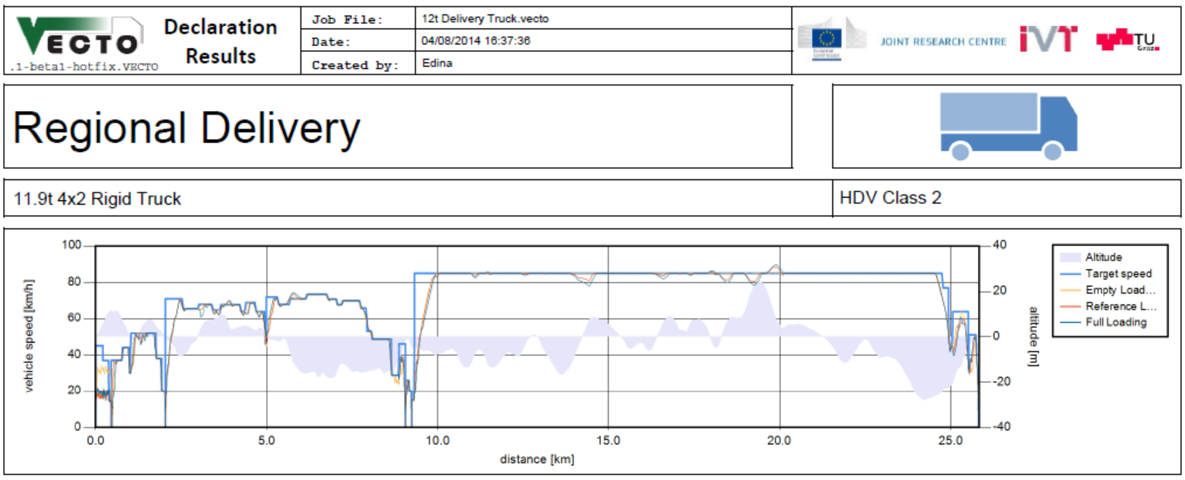
Table A3-4: Characteristics of main truck cycles

	Distance	Average target speed	Duration of stops
20120815_acea_urban_delivery_1m	27.8 km	38.3 km/h	635 s
20120815_acea_regional_delivery_1m	25.8 km	74.6 km/h	110 s
20120815_acea_long_haul_1m	108.2 km	82.1 km/h	240 s
20120828_acea_construction_cycle_1m	21.2 km	60.4 km/h	646 s

Source: Ricardo-AEA from on-going research for the European Commission on the development of the VECTO tool.

The vehicle speed - distance graph for an 11.9 tonne truck for various loads when driven over the regional delivery cycle, is shown in Figure A3-5. Dividing the distance by the speed would convert the speed – distance graph into a speed – time plot.

Figure A3-5: Vehicle speed-distance – 11.9 tonne truck for various loads (regional delivery cycle)



VECTO **Declaration Results**
.1-beta1-hotfix.VECTO

Job File:	12t Delivery Truck.vecto
Date:	04/08/2014 16:37:36
Created by:	Edina

Regional Delivery

11.9t 4x2 Rigid Truck

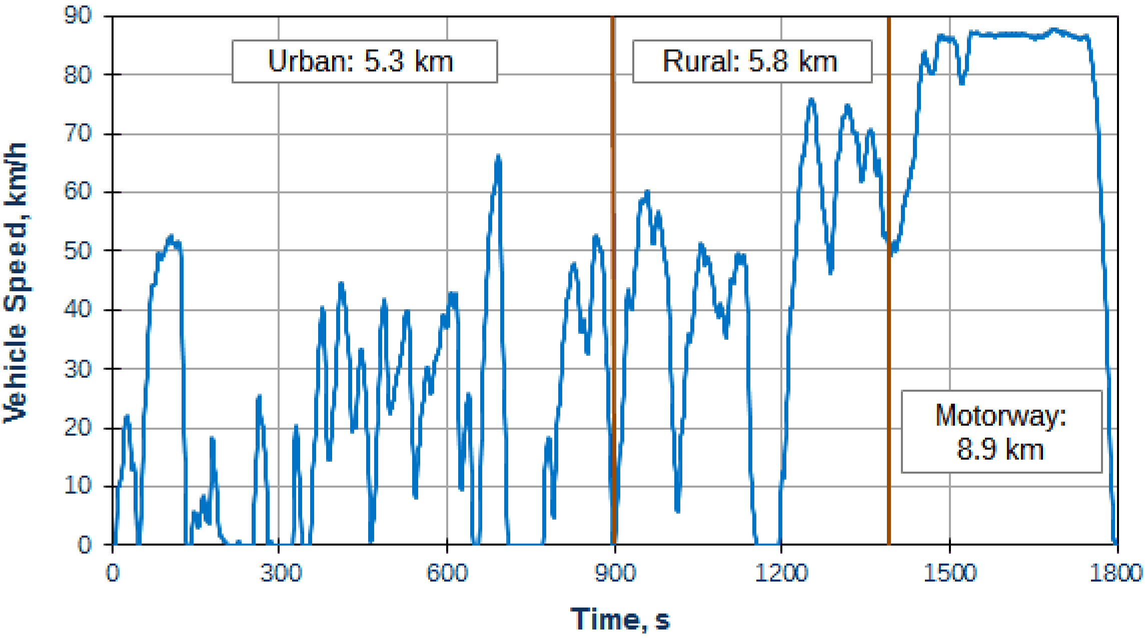
HDV Class 2

Source: Ricardo-AEA from on-going research for the European Commission on the development of the VECTO tool.

World Harmonised Vehicle Cycle (WHVC)

The WHVC is a chassis dynamometer cycle originally designed as an intermediate step between vehicle operational profiles and the engine-based WHTC. It is not a standardised cycle and is not used for regulatory testing. It is, however, a cycle in its own right and is accepted by industry to give a rough estimate representative of the emission performance of an engine in real-world use (AVL, 2014). The vehicle is pre-conditioned before the test, stabilising coolant temperatures (above 70°C) or exhaust temperatures. Emission performance can be recorded either in g/km or g/kWh (using quantification of executed work during the WHTC from the dynamometer sensors) over the 30 minutes the test is run. The test is performed over three sections, as shown in Figure A3-6, and has the following properties[76]:

Figure A3-6: World Harmonised Vehicle Cycle (WHVC)



Source: Dieselnet, 2013

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[76] To the nearest second, or km/h.

- Urban driving: 900 seconds duration, with an average speed of 21 km/h and a maximum speed of 66.2 km/h. This segment includes frequent starts, stops and idling.
- Rural driving: 468 seconds duration, with an average speed of 44 km/h and a maximum speed of 75.9 km/h.
- Motorway driving: 432 seconds duration at an average speed of 77 km/h and a maximum speed of 87.8 km/h.

Having distinct sections like this allows trivial identification of whether the vehicle performs poorly over certain speed ranges and can give insight into a vehicle's performance under various applications. For example, if the test cycles reveal an emissions spike within the urban section of the test then the vehicle may not be suitable for start-stop applications such as refuse collection.

Accreditation Scheme for aftermarket truck technologies under development by the Low Carbon Vehicle Partnership

The Low Carbon Vehicle Partnership (LowCVP) is developing the test procedures and an evidence base to underpin a proposed Accreditation Scheme for aftermarket low-carbon truck technologies. The scheme aims to provide a standardised approach to independently validate the fuel consumption savings offered by low carbon retrofit devices under a range of operating conditions and provide reassurance to commercial operators that they will see a return on their investment in the technology. One feature of the LowCVP's work thus far has been to develop a test process using cycles that are believed to adequately represent typical UK operating duties and correlate appropriately with the VECTO cycles. Another key feature is that this correlation exercise is being used to create a non-facility dependant test process, allowing comparable results from different test facilities.

The full details of the Accreditation Scheme have yet to be finalised, however it is likely to be based on track testing using fuel consumption meters and PEMS. Three provisional cycles have been developed, which are designed to reflect the three main truck cycles of the VECTO approach, namely urban delivery, regional delivery and long haul (but in doing so can vary from one facility to another in their speed-time profiles). The aim would be to run the truck over the cycles before and after the low-carbon retrofit technology has been fitted. The difference between the two test results would give an indication of the fuel savings offered by the retrofit technology, and other emissions could also be measured.

Appendix 4

Methods of analysis used in PEMS equipment

One of the principal constraints on PEMS equipment is the requirement to remain as unobtrusive to the test as possible. The weight of the equipment must be minimised as to add the least possible engine load and to minimise any effects on vehicle dynamics. The size of the PEMS equipment must be small enough to ensure that it does not illegally obstruct the driver's on-road visibility; power consumption should be insignificantly low or independent of the vehicle so as not to put extra load on the test vehicle's electrical system/alternator, etc. In addition, the legislation demands that PEMS must analyse in-real-time providing second-by-second outputs, so the use of constant volume sampling (CVS) bags is not possible and analysers must be present on board. Of significant importance is the response time of each detector which should be of the order of seconds[77] for transient testing – considerably faster than much of the equipment used in laboratory settings with CVS bags. The detectors must be accurate[78], precise[79] and exhibit little noise as dictated by clause 9.3.1.4 of (UN ECE, 2014). To achieve this, manufacturers have used innovative methods to convert traditionally very large equipment into modularised analysers.

The measurement principles of the analysers to be used are specified in section 9.3.2 of Annex 4 of Regulation 49 of the UN/ECE (UN ECE, 2014). (This is a live document, updated by WP.29, the World Forum for Harmonisation of Vehicle Regulations.) It is the regulation referred to within the EC Regulation (EC) 582/2011 for the specification of PEMS equipment. This forms part of Annex 4, Test Procedure, to Regulation 49. Equipment specification and verification is given in Annex 4. Table A4-1 summarises the order these are specified in and the type of analyser that is to be used.

Table A4-1: Analysis techniques to be used for different gaseous species, from UN ECE Regulation 49

Analysis	Section of Annex 4 that describes this	Type of analyser to be used
Carbon monoxide analysis	9.3.2.2	Non-dispersive infrared absorption
Carbon dioxide analysis	9.3.2.3	Non-dispersive infrared absorption
Hydrocarbon analysis	9.3.2.4	Heated flame ionisation detector
Methane and non-methane hydrocarbon analysis	9.3.2.5	Heated non-methane cutter & two flame ionisation detectors
Oxides of nitrogen	9.3.2.6	Either chemiluminescence detector or Non-dispersive ultraviolet detector
Air to fuel measurement	9.3.2.7	Wide range air to fuel sensor or Zirconia type lambda sensor

CO and CO_2 analysis

Carbon monoxide (CO) and carbon dioxide (CO_2) emissions can be measured most simply by non-dispersive infrared absorption spectroscopy (NDIR). NDIR analysers provide effective measurement with high stability, fast response times, long lifetimes and at a relatively low cost.

Infrared radiation from a broadband emitter is tuned to either a CO, or CO_2 absorption line using an optical band pass filter. This is passed through the source and its attenuation measured. This is then converted to give a gas concentration via the Beer-Lambert law. The drawback of the NDIR technique is its limit of detection: the filter bandwidth is wider than the desired absorption line. Other gaseous species may also absorb infrared radiation at energies close to those absorbed by CO, or CO_2.

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[77] Analyser rise time must not exceed 2.5 seconds.

[78] Deviation from the reference value must not exceed ±2% of the reading, or ±0.3% of full scale: whichever is larger.

[79] The precision (2.5 times the standard deviation of 10 repetitive responses to a calibration gas) must be ≤1% of full scale for each range used above 155ppm, or ≤2% of each range used below 155ppm.

Furthermore, background noise and cross-sensitivity can constrain the detection limits. Condensation from exhaust gases absorbs all IR radiation and will severely inhibit the results, so preconditioning and/or temperature control are required[80].

In addition frequent calibration is needed - even though reference beams are often used, NDIRs suffer from zero and span drifts as they measure only relative absorption and are affected by atmospheric changes. Recent work[81] has, however, demonstrated the potential to improve the sensitivity of NDIR analysers to the very low ppm levels required by automotive emissions legislation, although examples could only be found in academic literature and a commercialised unit has not been seen.

(Total) hydrocarbon analysis (T)HC

Hydrocarbon concentrations can be quantified using infrared or flame ionisation detection. The infrared techniques include NDIR, as for CO and CO_2, Fourier Transform infrared (FTIR) spectroscopy. However, as can be seen from Table A4-1, Regulation (EC) 582/2011, through UN ECE Regulation 49, restricts the type of analyser that can be used for the measurement of hydrocarbons in automotive exhaust to flame ionisation detectors (FIDs).

The pyrolysis of the exhaust stream in a hydrogen flame generates hydrocarbon ions. These are detected as a current between metal collector plates biased with a high DC voltage. This mechanism allows an FID to measure the total hydrocarbon content of a sample gas. The electrical current produced (on the order of pico-amps) corresponds roughly to the proportion of reduced carbon atoms in the flame and after amplification, electrical integration and processing offers concentration measurement in the tens of parts per million. The main benefit of FIDs is that they are suitably effective and inexpensive – however they do require various gases for operation and frequent calibration.

FIDs are relatively robust and withstand the harsh environment on-road testing presents, requiring minimal maintenance and coping with a wide range of inputs. Operating conditions must be monitored, however, as FIDs produce a considerable amount of water vapour which can condense in the unit at low operating temperatures, producing noise and drifts unless the internal temperature is regulated. This is why the analyser specification mandates the use of **heated** FIDs. The warm-up time of these devices is notably long (up to an hour) and response times were originally slow (a few seconds) but these drawbacks have been improved through appropriate design improvements. ‘Fast-response FIDs’, with a response time of milliseconds are now available. Naturally, as FIDs oxidise the exhaust gas hydrocarbons to form carbon dioxide and water this is a ‘destructive’ test and consequently it must be carried out at the end of the analysis chain.

It is worth noting that tailpipe hydrocarbon emissions are measured in the UK as part of the long-standing MOT test. Inexpensive NDIR detectors (a few thousand pounds) are used to give a fair measure of the THC levels, allowing suitable determination for the annual roadworthiness emissions checks but these instruments have insufficient accuracies and repeatability for the type approval test.

Methane (CH_4) analysis

Methane emissions can, like other hydrocarbons, be measured most simply by non-dispersive infrared absorption spectroscopy, in a manner analogous to that used for CO and CO_2. However, as for other hydrocarbons, and as can be seen from Table A4-1, Regulation (EC) 582/2011, through UN ECE Regulation 49, mandates that the type of analyser that can be used for the measurement of methane is a FID (this was described in the previous sub-section). The specified analyser arrangement uses two FIDs and a heated non-methane cutter, as shown schematically below.

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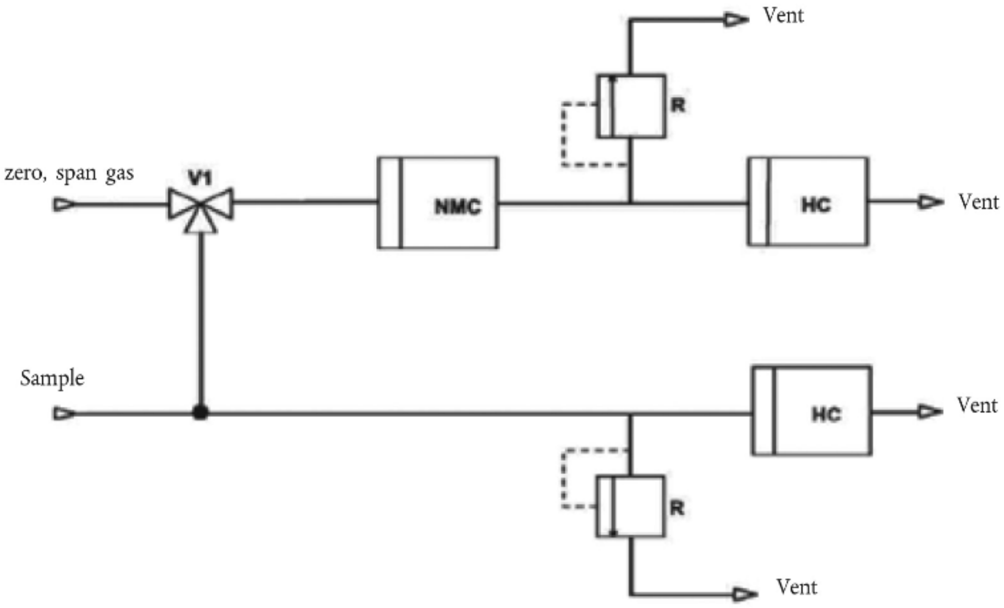
[80] Clause 9.3.2.6.2 of (UN ECE, 2014)

[81] For example: 1ppm **Invalid source specified.**, 8ppm**Invalid source specified.**.

Figure A4-1 - Schematic flow diagram of methane analysis with the non-methane cutter



Source: UN ECE Regulation 49

One stream of gas is fed through a hydrocarbon removal catalyst (or ‘non-methane cutter’) which converts most of the non-methane hydrocarbons to CO_2 and water. These do not undergo combustion in the FID and so are not detected. The other gas stream, fed directly to the second FID measures total hydrocarbon content (THC) (including methane). This approach works because of the relative resistance of methane to oxidation, see Another factor, evident from the chemical equations for the oxidation of methane and other hydrocarbons, is that methane requires more oxygen, and consequently more air, for its oxidation.

Figure 2-4, which makes it possible to selectively oxidise (remove) the non-methane hydrocarbons.

This approach requires a second FID, and its associated services and power consumption, and a non-methane cutter, a heated catalyst. It adds

Use of a single FID for methane detection

For a dedicated methane vehicle, while Table 1-3 indicates that the type approval limit is 160 mg/kWh for NMHC and 500 mg/kWh for methane. This gives a methane to non-methane HC ratio of 3.125, whilst previous studies have indicated that the ratio for dedicated CNG vehicles fitted with a three-way catalyst, is actually much higher. (Hestenberg, 2009) gives average emissions from four vehicles as 0.29 g/mile for NMHC, and 2.75 g/mile for methane. Recent advances to further reduce methane emissions will also reduce other HC emissions, most probably by a larger factor. Consequently, for dedicated methane vehicles use of a single FID and presuming that THC is a reasonable proxy for methane emissions is not too inaccurate.

Some dual-fuel vehicles, however, exhibit a much poorer methane slip performance. However, as is noted in Chapter 5, where the performance of comparator vehicles is considered, their THC emissions are typically below 0.05 g/kWh. So for dual fuel vehicles, the use of a single THC FID and the assumption that THC is a reasonable proxy for methane emissions is a more accurate assumption than for dedicated methane vehicles, and would be appropriate for a measurement protocol that sought to identify vehicles whose methane slip cancelled out the CO_2 reduction cause by substituting some diesel fuel with methane.

Further discussion on this, particularly focussed on this methane slip protocol's requirements, are given in Chapter 7, where the reliability of testing is considered.

Nitrogen Oxides (NO, NO_2) analysis

UN ECE Regulation 49 specifies two alternatives for measuring oxides of nitrogen, NOx:

- Chemiluminescent detector (CLD) and
- Non-dispersive ultraviolet (NDUV) analysers

For the three PEMS available two use NDUV and one used CLD.

Chemiluminescent detector (CLD)

These measure NO concentration directly, detecting the luminescence signal generated when NO reacts with ozone (O_3) using a photomultiplier tube. NO_2 is measured indirectly; it is quantitatively converted to NO, and then the entire NO sample is measured (i.e. NO + NO_2, or NOx). If the non-converted NO reading is subtracted from to total NOx reading this gives the NO_2 value initially present in the exhaust gas.

CLDs are advantageous in their impressive detection limit – laboratory units can have sensitivities in parts per trillion, however PEMS equipment often uses sensitivities of 0-10,000 ppm (DieselNet, 2014) where this high sensitivity is not used. CLDs have rapid response times, are able to monitor continuously, have linearity over a wide dynamic range and moderately simple. Unfortunately, the chemiluminescence reaction requires carefully managed operating conditions and initial calibration: it is very sensitive to the rate of gas flow (necessitating separate systems for ozone and NO), the ozoniser requires very high, stable temperatures (up to 800°C) and the photomultiplier requires very high voltages. The signal from CLDs are also susceptible to quenching, where light from the reaction is absorbed by other gases in the sample (principally CO_2 and water) which will result in a reading of lower emissions[82]; a similar effect arises from a small proportion of allowable reactions between NO and O_3 where light is not released (Jernigan, 2002). Other photochemically-formed nitrogen oxides can act to give an overestimation, detracting from the accuracy of the method (Kleffmann, Villena Tapia, Bejan, Kurtenbach, & Wiessen, 2012). As the gas is modified using this method the CLD must be stationed at the end of the analytical chain.

Non-dispersive ultraviolet (NDUV)

An alternative method of NOx measurement method is to use non-dispersive ultraviolet (NDUV) analysers. The operating principles of NDUV units closely match that of the NDIR equipment, but replace infrared with ultraviolet radiation. This is required to measure the absorption lines of NO and NO_2 and minimises cross-sensitivity issues because CO_2 and water are only weakly absorbed at UV wavelengths. As such, NDUVs share many of the benefits and pitfalls of NDIR analysers, however can provide better resolution (<1ppm). Beneficially, NDUVs do not require the complicated ozoniser and NO_2 conversion auxiliaries which CLDs incorporate; nor do they consume as much power.

Figure A4-2 - Schematic layout of an NDUV analyser. The EDL is a UV source.

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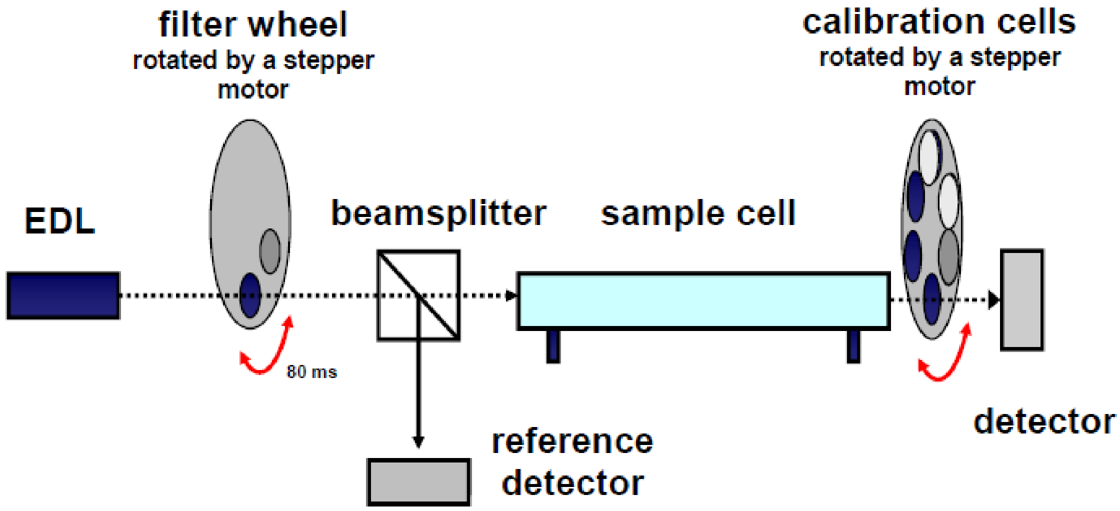
[82] The quench may not exceed 2% of the expected NO_x concentration during testing (clause 9.3.2.6.2 of (UN ECE, 2014)



Source: (AVL, 2012)

Oxygen (O_2)

Oxygen is paramagnetic, whereas most other exhaust gases are not, and thus is simply measured using a paramagnetic analyser. This means than cross-sensitivity is virtually negligible and the device comfortably provides a suitably sensitive measurement for regulation (detection limits can be <50ppm, or 0.1vol% at response times of ~1Hz) (Krippner, Andres, Szasz, Bauer, & Wetzko, 2014). Paramagnetic analysers cannot be poisoned, but are sensitive to water vapour and are more expensive than their electrochemical competitors.

Electrochemical oxygen sensors, a basic form of fuel cell, are much cheaper than paramagnetic sensors but have longer response times, high cross-sensitivities and low chemical resistance (e.g. to sulphur compounds and even trace ammonia levels in the exhaust gas). For this reason they have lifespans of only a few years. They are able to comply with current regulation, having sensitivities of ppm magnitude. Electrochemical cells are moderately sensitive to ambient temperature.

Particulate matter (PM) and particulate number (PN)

It is noteworthy that the section of Regulation (EC) 582/2011 that specified the test parameters requiring instantaneous measurement by PEMS unit (see Table 3-3) does not include any measurement of particulate mass or particle number (UN ECE Regulation 49 specifies the measurement procedures to be used for type approval, dynamometer testing).

Therefore, whilst some manufacturers are developing these measurement capabilities, they will not be detailed further in this study because they would not form part of the methane slip test protocol.

Examples in the market place

Although there are a number of PEMS suppliers, particularly those producing modular analysers for specific emissions[83], it is considered[84] that there are currently three main competitors in the UK automotive sector offering comprehensive PEMS packages. In alphabetical order, these are AVL, Horiba and Sensors, Inc. Each company produces emissions systems compliant with the UN ECE R-49, EC Regulation 582/2011 and 40CFR part 1065 legislation; each is currently in use at major automotive testing facilities in the UK. Their PEMS-specific capabilities are summarised in Table 3-4.

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[83] Especially particulate counting – 3DatX, Matter Aerosol and Pegasor for example.

[84] This became clear after discussions with various UK-based PEMS operators.

Table A4-2: – PEMS unit capabilities from three major manufacturers.

Parameter	AVL	Horiba (OBS-ONE-GS11 and GS12)	Sensors, Inc. SEMTECH ECOSTAR (EFM 2)
CH_4	N/A	N/A	Dual FID (0-100 to 0-40000ppmC)
CO	NDIR (0–5% vol.)	Heated NDIR (0-0.5 to 0-10% vol.)	NDIR (0-8.5% vol.)
CO_2	NDIR (0–20% vol.)	Heated NDIR (0-5 to 0-20% vol.)	NDIR (0-18% vol.)
NO	NDUV (0–5000ppm)	Heated-dual CLD (0-100 to 0-3000ppm)	NDUV (0-3000ppm)
NO_2	NDUV (0–2500ppm)	Heated-dual CLD (0-100 to 0-3000ppm)	NDUV (0-500ppm)
O_2	Electrochemical	N/A	Electrochemical or paramagnetic
PM	Photo-acoustic detector[a] (≤10µg/m^3) and GFM (0.005-50 mg/m^3)	Diffusion charging analyser[b] (0-2500mm/cm^3) and GFM	Ion mobility technique analyser[c]
PN	Photo-acoustic detector (≤10µg/m^3)	✓	Ion mobility technique analyser
THC	Heated FID (0–30000ppmC)	Heated FID (0-100 to 0-10000ppmC)	Heated FID (0-90ppm to 0-30000ppm) or NDIR
Exhaust flow meter	Pitot flow meter	Pitot flow meter (0-2.0 to 0-65.0 m^3/min)	✓
Flow tube max flow rate[d] (m^3/min), @flow tube diameter	-	17 @3” 31 @3.5” 48 @4”	20 @3” 25 @4” 30 @5”
Exhaust temperature	✓	✓	✓
Maximum exhaust temperature	-	500°C	550-700°C [e]
Exhaust pressure	✓	✓	0.025–16.5kPa
Operation time	-	~4.5 hours	~2.5 hours

Parameter	**AVL**	**Horiba (OBS-ONE-GS11 and GS12)**	**Sensors, Inc. SEMTECH ECOSTAR (EFM 2)**
Operating conditions	-30 to 45°C	-10 to 45°C	-10 to 45°C
Zero drift: O_2	-	-	< 0.1%vol / 1h
Zero drift: THC	< 1ppm / 8h	-	< 1% of range / 1h
Zero drift: NO	< 2ppm / 8h	-	< 2ppm /1h
Zero drift: NO_2	< 2ppm / 8h	-	< 2ppm / 1h
Zero drift: CO	< 20ppm / 8h	-	< 50ppm / 1h
Zero drift: CO_2	< 0.1%vol / 8h	-	< 0.1%vol / 1h
Heated sample lines	✓	✓	✓
Fuel consumption	✓		✓
GPS (incl. speed)	✓	✓	✓
Ambient humidity	✓	✓	✓
Ambient temperature	✓	✓	✓
Ambient pressure	✓	✓	✓
SAE-J1708 compliance[f]		✓	✓
SAE-J1939 compliance[g]		✓	✓
OBDII interface	✓	✓	✓
ISO 15765 compliance[h]		✓	
ISO 27145 compliance[i]			✓
Vibration isolation	✓	✓	✓

Notes to Table A4-2.

[a] MSS “Micro Soot Sensor”. The MSS up-scales the continuous signal of some particulate property.

[b] OBS-TRPM “Transient Particulate Matter”.

[c] PPMD “Portable Particulate Measurement Device”.

[d] At 25mbar backpressure, 200°C exhaust temperature.

[e] EFM-HS non-standard.

[f] HDV ECU serial communications standard

[g] Vehicle bus communication standard

[h] Data packet protocol over CAN-bus standard

[i] Communication standard for vehicle on-board diagnostics – required by WWH-OBD

Source: Manufacturer websites and associated brochures as of November 2014. This list is compiled from multiple sources and may not be complete.

Appendix 5

Track based test procedure

TRACK BASED TEST PROCEDURE

INTRODUCTION

The purpose of this procedure is to define the test method to ensure correct vehicle set-up and process required to conduct accurate and repeatable track based fuel economy and emissions testing.

SCOPE

This process should be followed every time a track based fuel economy and emissions programme is conducted. Although various steps may have to be adapted to account for variations in test requirements i.e. vehicle architecture changes, test cycles, gear change points, etc. The basic step by step process should always be adhered to. This will eradicate any controllable events effecting the accuracy and repeatability of the test results.

DETAILED PROCEDURE/REQUIREMENTS

Upon arrival of test/control vehicle, a vehicle check and road test is to be conducted to assess suitability of vehicle to undergo testing of this nature. This check will also include fluid level checks and correct adjustment of tyre pressures

Depending upon chosen test criteria, instrument and prepare test/control vehicle with the following equipment as required;

- Thermocouples to accurately record the following temperature parameters; Engine Oil, Transmission Oil, Differential Oil, Engine Coolant
- Data logger to record vehicle CAN bus data where available
- Calibrated instrument for recording vehicle speed and position (GPS System)
- Calibrated instrument to measure actual fuel usage (Fuel Flow Meter)
- Portable Emissions Measuring System (PEMS) to accurately measure vehicle tailpipe emissions & calculated fuel consumption via carbon balance method

Carry out vehicle shakedown check to confirm correct operation of all fitted equipment.

Safely and securely load test/control vehicle to required test weight.

The test procedure will be designed in the most appropriate way to best evaluate the product being tested.

Develop or adjust appropriate drive cycle(s) to customer requirements, including test route within the facility, vehicle speeds and gear change strategy.

Conduct driver familiarization runs to allow drivers to familiarize themselves with vehicle, cycle(s) and test equipment operation.

Await appropriate weather condition required to commence testing.

The vehicle(s) shall be suitably conditioned to achieve a stable test start point.

The testing shall be conducted in a manner to show repeatability and reproducibility of the test process over the test programme. Consideration shall be made to the test variables encompassing vehicle, ambient conditions, fuel, tyres, weight, wind resistance, etc.

All testing is to be conducted by trained drivers.

Example template for results obtained

	THC or CH4 emissions	CO_2 emissions	Fuel consumption
Vehicle in dual fuel mode			
Urban (1st cycle)			
Rural (1st cycle)			
Motorway (1st cycle)			
Combined (1st cycle)			
Urban (2nd cycle)			
Rural (2nd cycle)			
Motorway (2nd cycle)			
Combined (2nd cycle)			
Urban (3rd cycle)			
Rural (3rd cycle)			
Motorway (3rd cycle)			
Combined (3rd cycle)			
Average of three cycles for all 3 separate components and for the whole combined cycle			
Standard deviation for the three cycles for all 3 separate components and for whole combined cycle			
Vehicle in diesel only mode			
Urban (1st cycle)			
Rural (1st cycle)			
Motorway (1st cycle)			
Combined (1st cycle)			
Urban (2nd cycle)			
Rural (2nd cycle)			
Motorway (2nd cycle)			
Combined (2nd cycle)			
Urban (3rd cycle)			
Rural (3rd cycle)			
Motorway (3rd cycle)			
Combined (3rd cycle)			
Average of three cycles for all 3 separate components and for the whole combined cycle			
Standard deviation for the three cycles for all 3 separate components and for whole combined cycle			

The average components above can then be weighted to model representative GHG emissions for the type of vehicle being tested. For an articulated truck driving predominantly on truck roads and motorways it might be appropriate to use:

20% urban cycle + 20% rural cycle + 60% motorway cycle.

In which case the calculation would follow:

GHG emissions in dual fuel mode:

CO_2 = 20% * average of three cycles for urban plus rural components when in DF mode+
60%* average of three cycles for urban plus rural components when in DF mode

CH_4 = 20% * average of three cycles for urban plus rural components when in DF mode+
60%* average of three cycles for urban plus rural components when in DF mode

GHG emissions = CO_2 emissions from above + 28 x = CH_4 emissions from above.

GHG emissions in diesel only mode:

CO_2 = 20% * average of three cycles for urban plus rural components when in diesel mode+
60%* average of three cycles for urban plus rural components when in diesel mode

CH_4 = 20% * average of three cycles for urban plus rural components when in diesel mode+
60%* average of three cycles for urban plus rural components when in diesel mode

GHG emissions = CO_2 emissions from above + 28 x = CH_4 emissions from above.

Impact of using methane fuelling

= GHG emissions in dual fuel mode - GHG emissions in diesel only mode

This will be a negative number if the GHG emissions in dual fuel mode **are less than** the GHG emissions in diesel only mode and a positive number if the GHG emissions in dual fuel mode are larger.

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