Air Quality Emissions Impacts of Low CO_2 Technology for Buses

Report for LowCVP

Date	**10 October 2013**
Report	**RD.13/125301.6**
Client Project Ref.	**Q003889**
Confidential	**Low Carbon Vehicle Partnership**

Report by **Richard Cornwell** **Signe Hulbert** **Jon Andersson** **Matthew Keenan**

Approved

David Greenwood

Product Group Head – Hybrid & Electric Vehicles

© Ricardo plc 2013

Contents

Approach

- Ricardo have compiled a Roadmap for LowCVP for low carbon technologies for buses. This has been reported in RD12/409701.5
- As an additional workstream, Ricardo were asked to comment on the likely Air Quality impacts of the low carbon technologies being proposed. This document is prepared in response to that request
- Ricardo have used the following data sources in preparing this document:
  - KBA database for bus engines 2012 (German Federal Transport Authority)
  - US EPA & CARB databases for bus/HD engine certification results
  - TfL Hybrid bus air quality emissions data kindly provided by LowCVP
  - TNO report MON-RPT-033-DTS-2009-03840
  - Ricardo engine benchmark database and information where not constrained by confidentiality
  - Ricardo expert analysis

Approach

- It should be noted that the bulk of the data available is engine emissions test results performed on engine dynamometer. Actual vehicle emissions test results in g/km based on chassis dynamometer tests is very rare in the public domain.
- The consequence of this is that it is easy to differentiate different engine technologies in terms of their impact on AQ, however quantifying impact on AQ of vehicle technologies is very difficult without test data. The TfL air quality study on hybrid buses is a rare example of good quality real-world vehicle test data
- Ricardo have taken the basic approach of assuming that any vehicle technology which reduces tailpipe CO_2 by reducing fuel burned, will have a proportional reduction in AQ emissions – the principle being: if less fuel is burned, fewer AQ emissions are produced on a g/km basis
- This approach has obvious limitations, therefore a conclusion of this study is that the bus industry should carefully assess by vehicle testing the real-world air quality impact of any low CO_2 technology which significantly alters the duty cycle of an emissions certified engine relative to the engine emissions test cycles

Contents

Air Quality Emissions

- AQ emissions are typically those substances regulated by “traditional” emissions regulations (i.e. Euro III, IV, V, VI etc.). In the US they are sometimes known as “criteria pollutants”
- As well as those “regulated” emissions, there are a family of substances known as “unregulated” emissions (or “unregs”) which may be of specific concern. If the concern becomes great enough, an unregulated emission may become a regulated emission
- A further complication is that some emissions regulations treat emissions differently depending on engine type. For example, diesel engine regulations in the US only are concerned with Non Methane Hydrocarbons (NMHC) so methane is an unregulated emission for diesels. If gas fuelled engines are certified to diesel regulations this can permit large emissions of unregulated methane
- By definition an unregulated emission is not covered by regulations, and public domain data typically only includes regulated emissions. Hence there is a high probability of emission of “unknown” substances, which only become the focus of attention if a specific health or AQ incident occurs

Emissions Impacting Air Quality (1)

Substance	What is it?	Impact	DieselStatus?	Gas Status?
NOx	Nitrogen oxides, including NO and NO2	Acidification, ozone forming, smog, N2O greenhouse gas (IPCC GWP_{100} = 298)	Reg	Reg
Pm	Particulate matter, soot, smoke, measured on a mass and number basis	Respiratory damage, global warming	Reg	Unreg at Euro V, becoming regulated at EEV & Euro VI
NMHC	Hydrocarbons (excluding methane), unburnt fuel	Smog, odour	Reg	Reg
Methane	Methane, unburnt fuel in gas engine	Smog, odour, potent greenhouse gas (IPCC GWP_{100} = 25)	Unreg	Reg
THC	Total hydrocarbon (CH4+NMHC)	Smog, odour	Reg (EU) Unreg (US)	Unreg
CO	Carbon monoxide	Toxicity	Reg	Reg
HCHO	Aldehydes from partially burned fuel esp. ethanol	Odour, respiratory damage	Unreg (EU) Semi reg (US)	Unreg
NH3	Ammonia slip from SCR	Odour, toxicity	Semi-reg	Unclear
PAH	Carcinogen associated with PM	Carcinogen	Unreg	Unreg

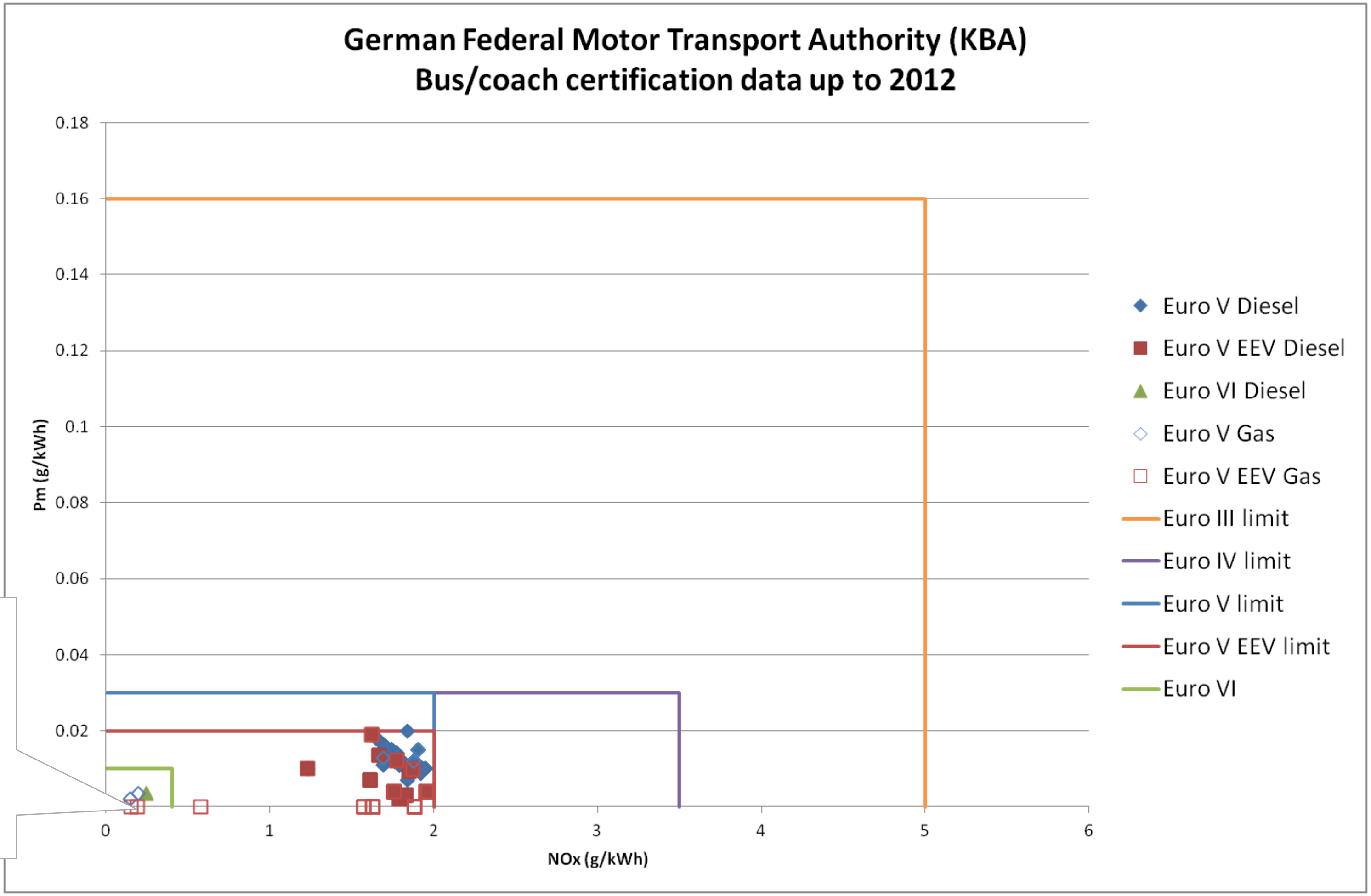
Emissions Impacting Air Quality (2)

Substance	What is it?	Impact	DieselStatus?	Gas Status?
Formic acid	Partial oxidation product	Odour, toxicity	Unreg	Unreg
Dioxins	Potential byproduct from some SCR catalysts	Toxicity	Unreg	Unreg
Hydrocyanic acid	Potential byproduct from some SCR catalysts, unproven	Toxicity	Unreg	Unreg
Nitrous oxide	Partial oxidation product, formed on catalyst, often of ammonia	Greenhouse gas, anaesthetic	Unreg	Unreg
Hydrogen Sulphide	Gas derived from sulphur in fuel and lubricant,	Odour, toxicity	Unreg	Unreg
Sulphur dioxide	Gas derived from sulphur in fuel and lubricant formed on catalyst	Odour, respiratory irritant	Unreg	Unreg
Benzene	Fuel component	Carcinogen	Unreg	Unreg
1,3-butadiene	Gas derived from partial combustion of fuel	Carcinogen	Unreg	Unreg

Contents

Air Quality impacts of different engine/fuel technologies – NOx/PM measured over legislative engine test

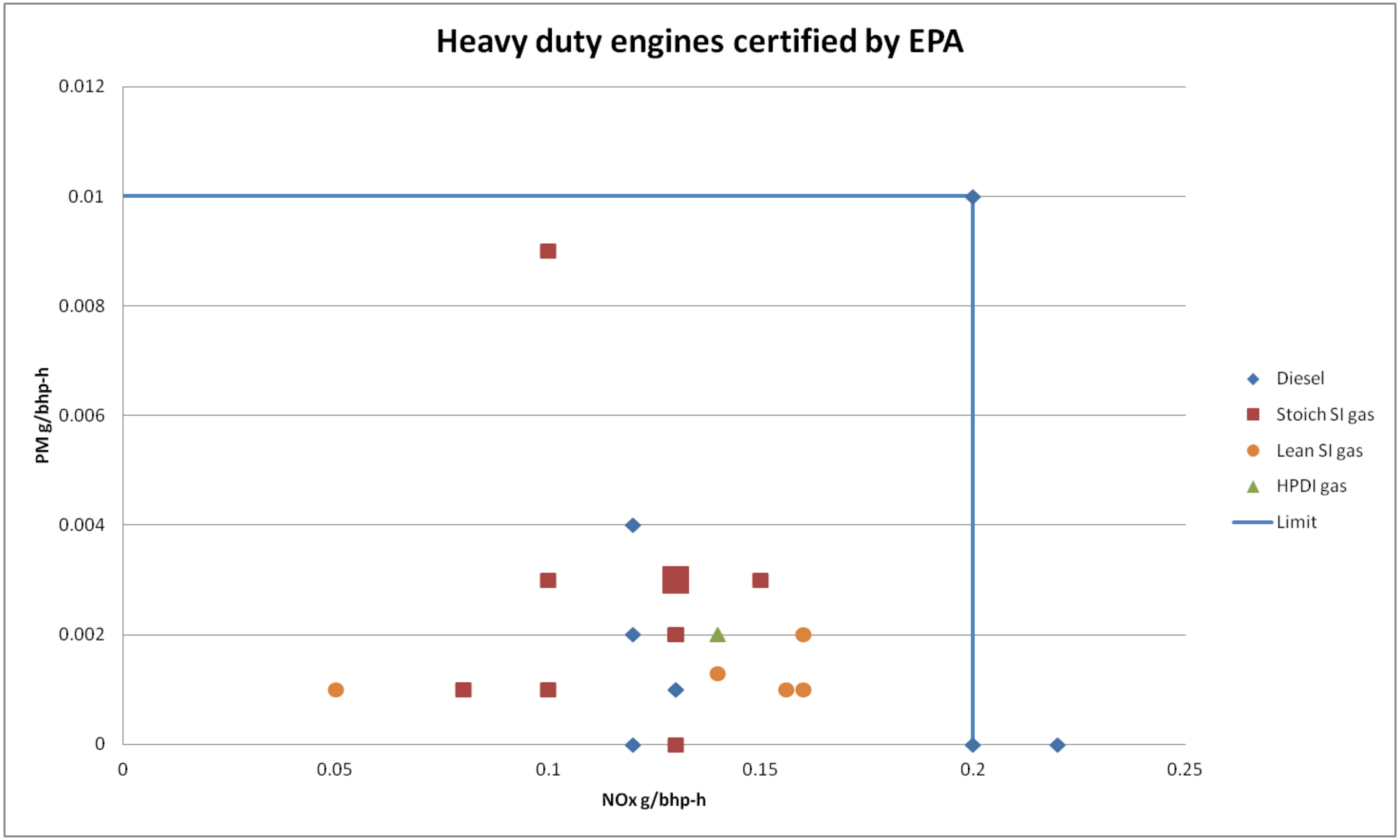
- At Euro V level there are some differences discernible, but by the time Euro VI is in force, diesel and gas are quite indistinguishable



PM measurement not required for gas engines so they appear as zero. They may emit PM though

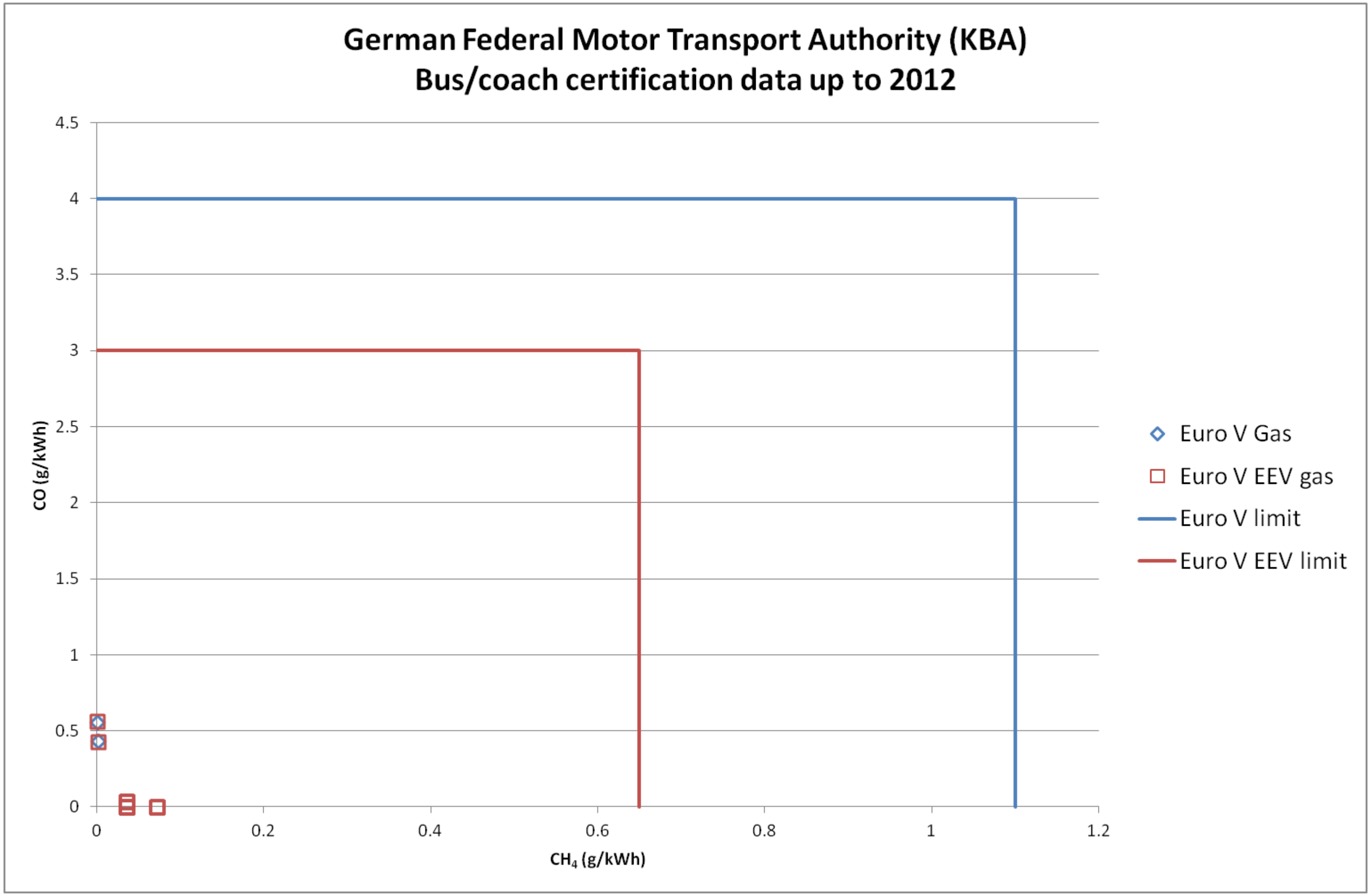
Air Quality impacts of different engine/fuel technologies – NOx/PM measured over legislative engine test

- The US data shows a similar story, at the extremely low levels currently in force, gas and diesel are very similar. Current EPA2010 limit shown. Note: 0.2g/bhph = 0.27g/kWh



Air Quality impacts of different engine/fuel technologies – HC/CO measured over legislative engine test

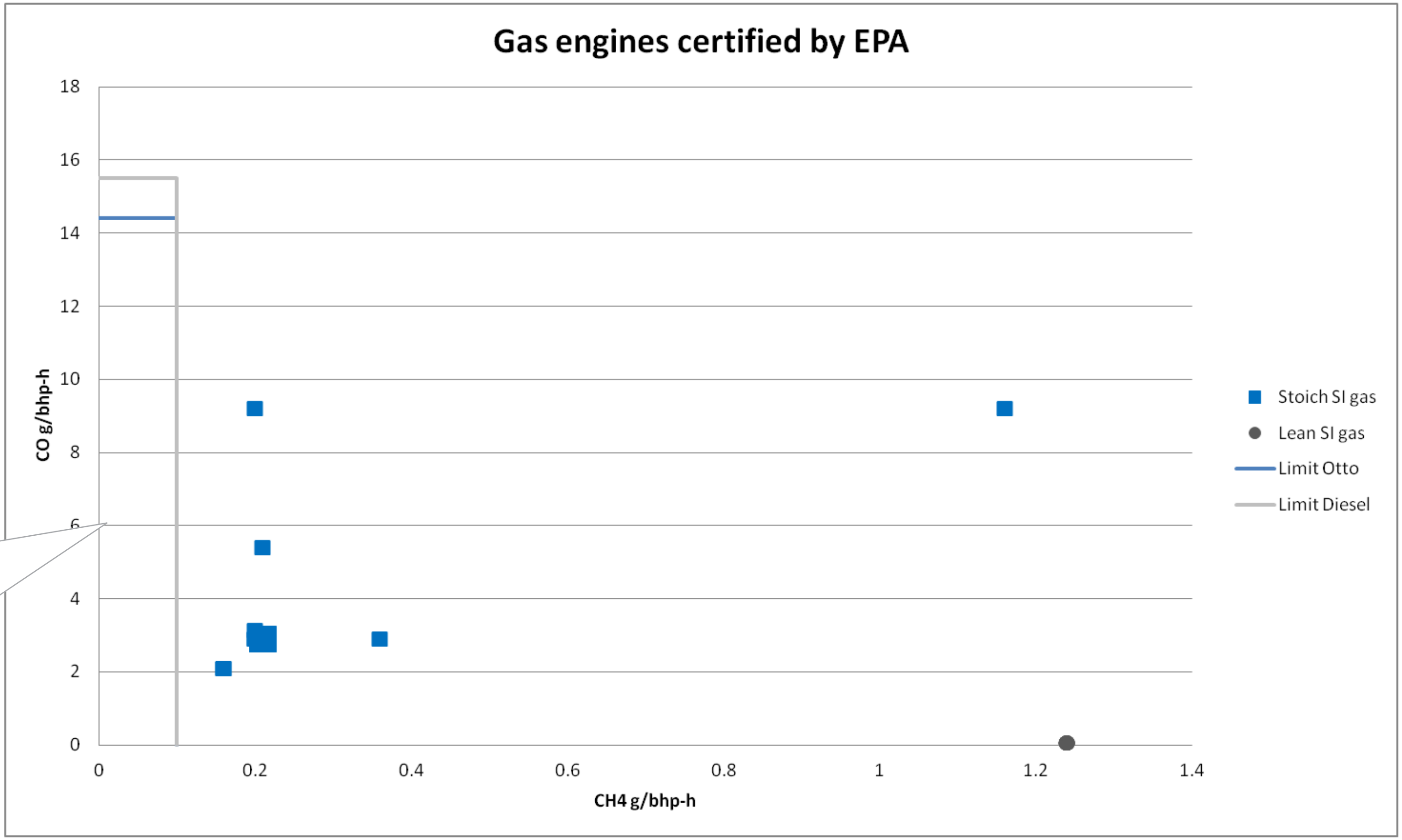
- Europe measures methane emissions for gas engines, forcing tight control



Air Quality impacts of different engine/fuel technologies measured over legislative engine test

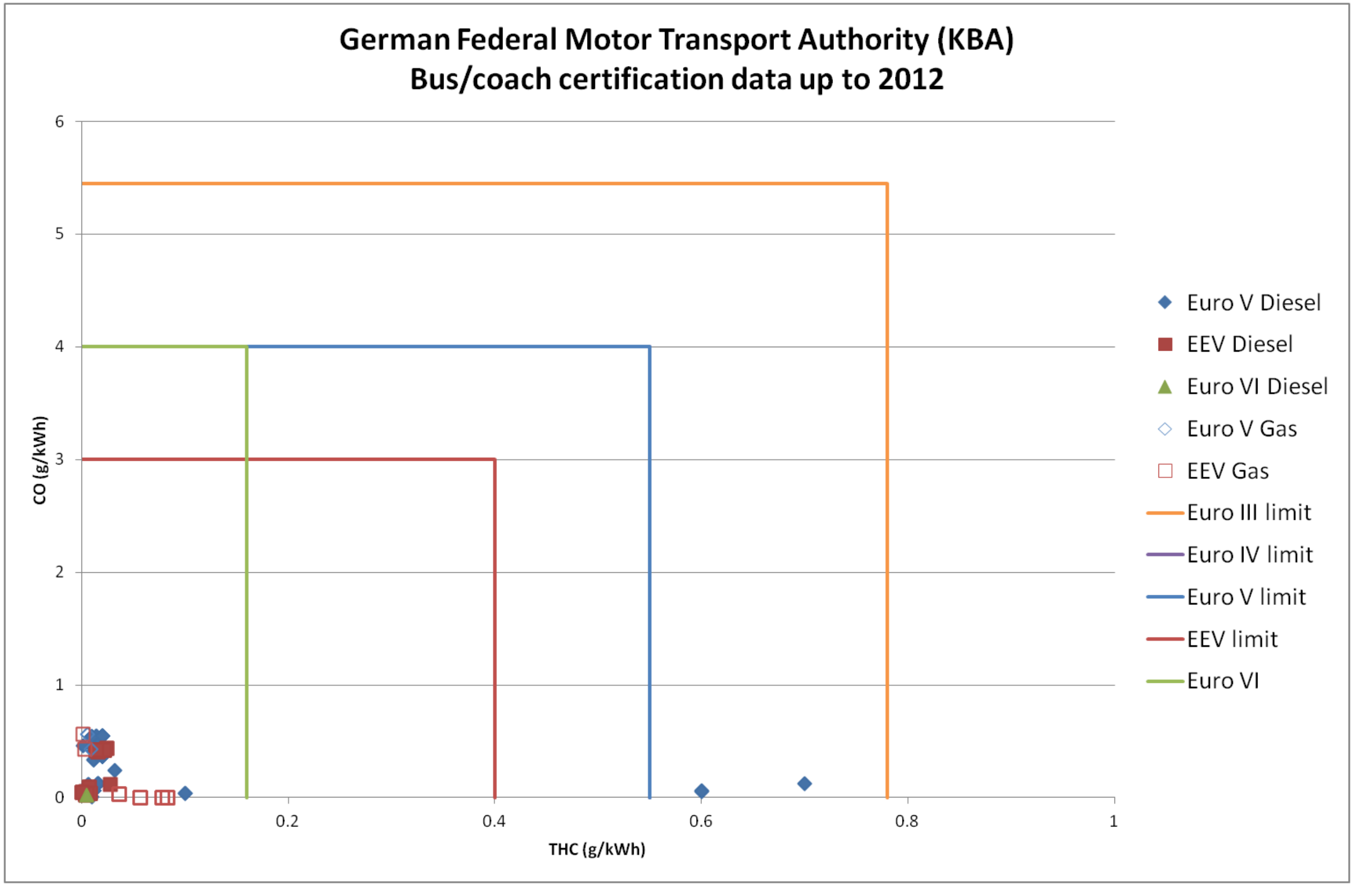
- CH_4 emissions are not directly measured for the EPA regulations. Hence some gas engines are permitted to emit large amounts of methane
- GHG emission standards (not air quality) will be phased in from 2014

GHG Limits to be implemented for CI in 2014 and for SI in 2016. EPA is allowing CH_4 and N_2O emissions to be offset against CO_2 credits



In Europe, Total HC emissions are regulated for Diesel engines, NMHC and CH_4 for gas engines

- HC/CH_4 – CO data of EU certified bus engines (THC = NMHC + CH_4)
- Because of the numerous ways of reporting hydrocarbons (HC, THC, NMHC, CH_4) the database is not clear/coherent, hence the data apparently showing limit exceedance

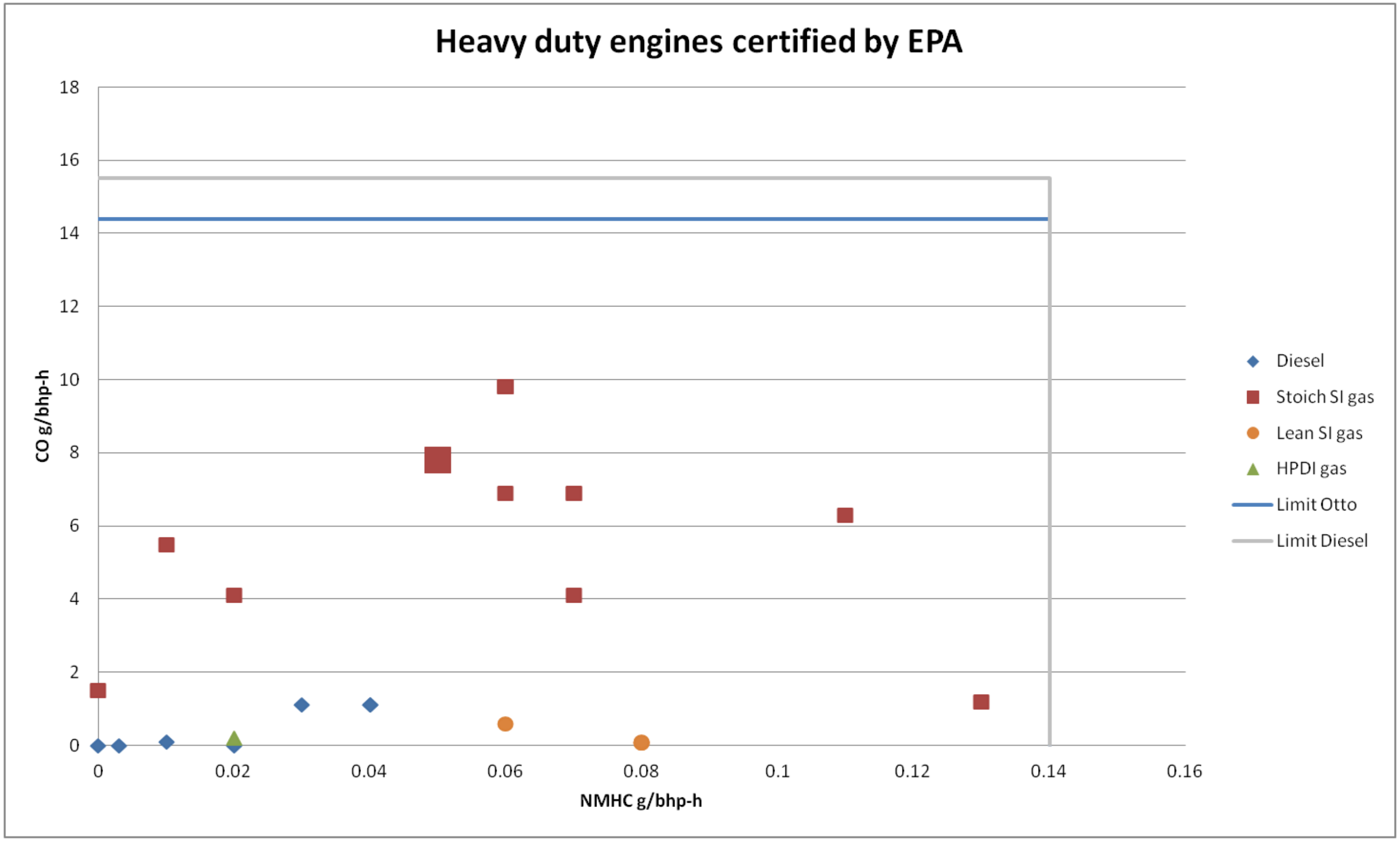


Source:

Air Quality impacts of different engine/fuel technologies measured over legislative engine test

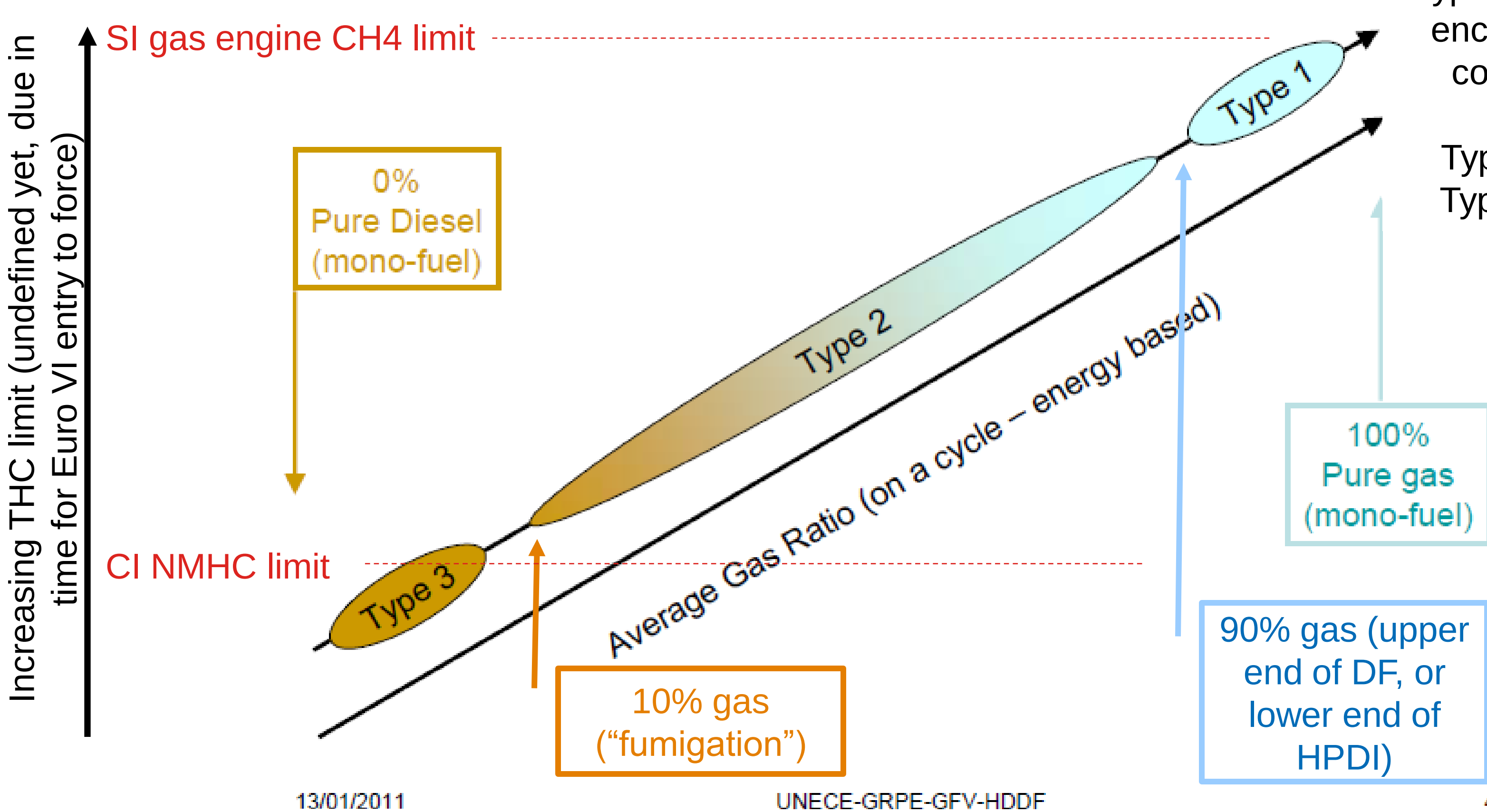
RICARDO

- HC/CH_4 – CO data of US EPA certified bus engines
- Because diesel regs only ask for NMHC, any gas burning engine certified to diesel regulations is permitted in principle to emit large amounts of CH_4



UNECE regulation is being proposed to cover dual fuel engines, to replace the current state-by-state interpretation in Europe

- UNECE GRPE (Work Party on Pollution & Energy) proposes 3 categories of gas/dual fuel engine. This should improve clarity of what is/isn't regulated for different fuels



Types definition:

Type 1 is a PI engine (actually encompasses SI and HPDI, could cover other ignition systems e.g. laser)
Type 2 is a true DF engine
Type 3 is rare/non-existent

Subtypes (for Type 1 & 2):

A) No diesel fallback
B) Diesel fallback

An engine with limited diesel limp home performance is deliberately time limited in that mode to effectively force it into subtype A)

Source: http://www.unece.org/trans/doc/2011/wp29grpe/GFV-12-03e.pdf

Some poorly integrated dual fuel engines can have significantly degraded air quality emissions

- A well integrated dual fuel (diesel/gas) engine will have communication between the base engine ECU and the gas metering controller, so that when running on gas, the diesel settings are optimised to maintain air quality emissions control
- Some poorly integrated dual fuel solutions can have serious air quality consequences, due to improper control of diesel fuel injection by adjusting rail pressure.
  - Reduced fuel injection pressure results in poor air-fuel mixing and high smoke/soot

Contents

 © Ricardo plc 2013

Air quality impacts of different vehicle technologies

- A basic rule of engine operation is, if a technology results in lower fuel burn rate, the air quality emissions on a g/km basis **should** reduce proportionately
- Therefore AQ impact of vehicle technologies **should** follow the Tailpipe CO_2 estimates given in the main low CO_2 roadmap report RD12/409701.4
- There are a number of reasons why this may not happen in practice
- Example: any technology resulting in periods of engine shutdown in combination with aftertreatment systems relying on achievement/maintenance of light-off temperature. An example of this may be a diesel hybrid bus with SCR because SCR efficiency may be significantly degraded if the exhaust is not hot enough because the engine is off for long periods
- However this effect will be totally dependent on duty cycle and **short** periods of engine off in hybrid mode is actually better for the catalyst than idle: operating at idle cools the catalyst due to flow through the catalyst. Engine off only allows radiative cooling, and consequently optimum catalyst operating temperatures are either restored more quickly on restart or are maintained during short idles
- The real world performance of temperature dependent aftertreatment should be validated for technologies such as hybrid or stop-start which significantly change the engine duty cycle

© Ricardo plc 2013

Data for MLTB test cycle operation of hybrid and conventional buses in g/km (TfL/Millbrook tests on single bus samples from fleets)

RICARDO

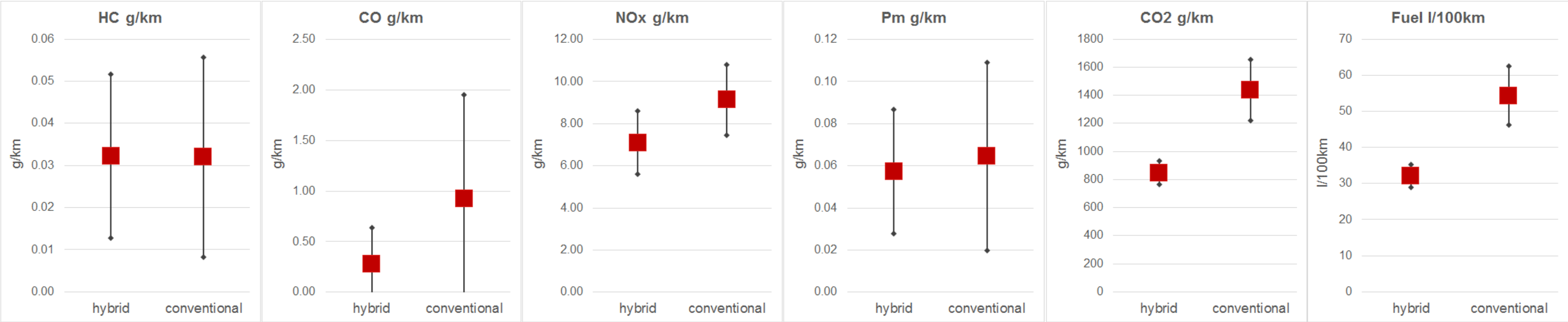
		Engine (from public domain sources)	Emissions Certification Level*	HC g/km	CO g/km	NOx g/km	PM g/km	CO_2 g/km	Fuel litre/100km
Wrightbus Gemini 1H	Siemens Series	GM 1.9 litre	Euro 4	0.012	0.039	7.616	0.06	866	32.800
Wrightbus Gemini 2H	Siemens Series	Ford Puma 2.4 litre	Euro 4	0.044	0.115	5.248	0.097	734.4	27.746
ADL Enviro 400H	BAE Series	Cummins ISB4.5	Euro IV	0.053	0.815	8.792	0.029	856.1	32.380
Volvo	ISAM	Volvo MD5	Euro V/EEV	0.02	0.152	6.738	0.043	937.3	35.400
Scania	Diesel EGR	Scania DC9	Euro IV	0.049	0.09	11.546	0.13	1572.1	59.380
Wrightbus Gemini 2	Diesel SCR	Cummins ISB6.7	Euro V	0.028	1.985	7.734	0.053	1250.6	47.350
ADL Enviro 400	Diesel SCR	Cummins ISB6.7	Euro IV	0.051	1.62	8.646	0.045	1253.1	47.600
Volvo B9TL / ADL	Diesel SCR	Volvo MD9	Euro IV	0.000	0.013	8.583	0.03	1670.3	63.080

- Engines for use in Light Duty Trucks (GVW <3.5t) are certified on a chassis dynamometer (with inertias and test weights determined by the vehicle specification). The GM and Ford engines are likely to have been certified to LDT standards (no HD certification for these engines is published in Kraftfahrt Bundesamt), as such they will not have emissions controls across the whole engine speed/load range

- Heavy Duty engines are certified on a test bed against test procedures referenced to the torque curve. The same basic engine may in real world be used for a low power duty cycle such as a city centre bus, or for a heavily loaded truck with a power to weight ratio of maybe 8 kW/tonne. The Cummins, Scania and Volvo engines will comply with the appropriate standards according to the emissions test cycle but may produce higher emissions on different duty cycles

© Ricardo plc 2013

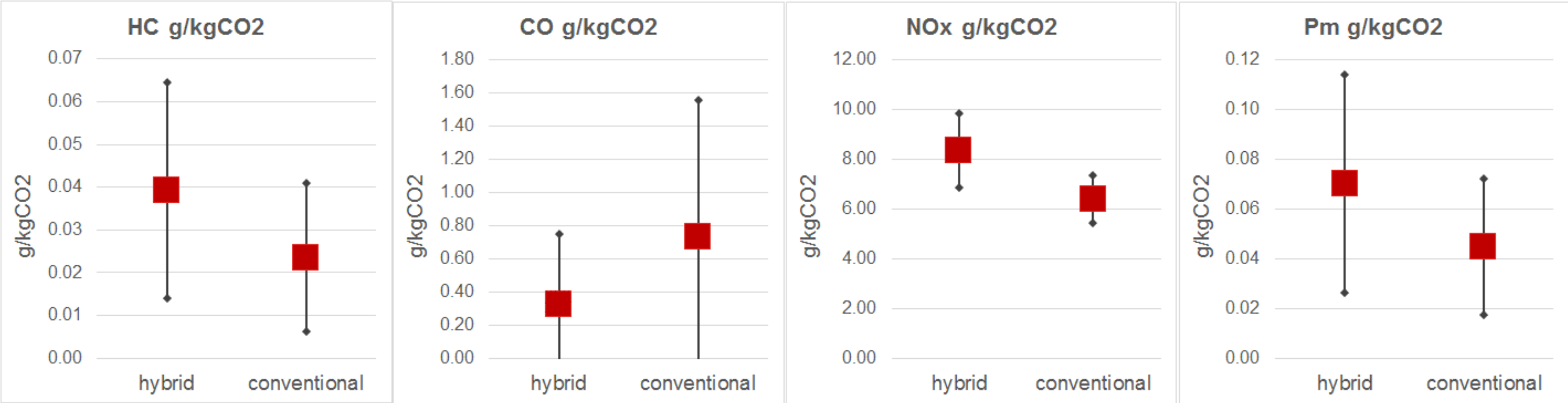
Measured emissions per km travelled over operating vehicle test cycle – hybrid vs conventional buses



Note: chart markers are average, error bars are +/- standard deviation

- Clearly the hybrid buses are making a significant impact on fuel consumption/CO2 emissions per km travelled. The error band (consistency across different models of bus) is much tighter also compared to the conventional buses.
- The chart shows that in all cases except for HC, the hybrid buses are performing significantly better than conventional buses in terms of absolute air quality emissions in grams per kilometre travelled.
- However, with the exception of CO, the proportional reduction of AQ emissions is somewhat less than the significant reduction in CO_2/fuel burned

Estimated relative emissions intensity per kg CO_2 emitted – hybrid vs conventional buses



Note: chart markers are average, error bars are +/- standard deviation

- In order to compare the hybrid and non hybrid technologies in terms of their emissions intensity (emissions produced per unit of fuel burned) the given data has been converted into g/kgCO_2. This method is the same used by the recent TNO report on real-world truck emissions
- These plots show that, excepting CO, the emissions intensity (gram per kgCO_2 emitted) is higher for the hybrid buses than conventional. In simple terms, the hybrid buses are doing well at reducing air quality emissions, but not as well as they could. This suggests a significant opportunity for hybrid buses to further improve their absolute emissions performance by reducing emissions intensity via improved powertrain / aftertreatment integration
- This increase in emissions intensity may be due to a greater dominance within the engine duty cycle of speed/load conditions away from the conditions seen on the ETC/ESC for which the engines will have been optimised. Put simply, the real world engine operating cycle in a hybrid bus may less closely match the legislative cycles the engines must meet, compared to a conventional bus. This is perhaps unsurprising, as the ETC cycle was originally derived from heavy duty conventional vehicle driving patterns (trucks & buses), not hybrids
- This discrepancy between real world and legislative cycles should reduce at Euro VI, since this legislation mandates a wide Not to Exceed (NTE) operating zone within which emissions must be within 150% of legal values

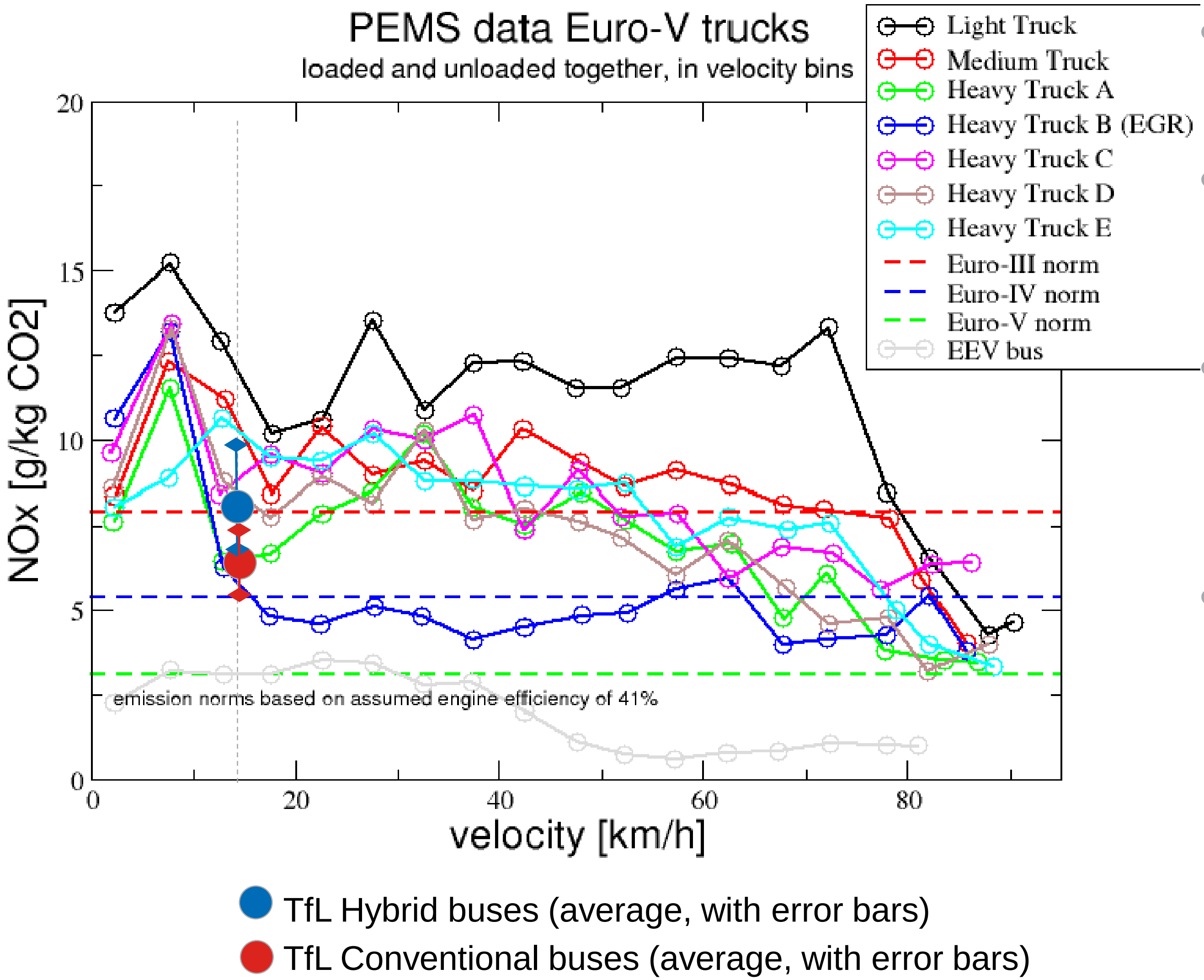
Reference: TNO report | MON-RPT-033-DTS-2009-03840, TfL Hybrid & Conventional bus data

© Ricardo plc 2013

In-use compliance of SCR is of concern for trucks, both EGR & SCR for buses

- There is concern within the European Commission and National governments that Euro V emissions requirements are not resulting in the legislative reductions in NOx being reflected in improved air quality. There is evidence that all types of heavy-duty vehicles do not exhibit legislative levels of specific emissions on real world driving cycles
- Air quality monitoring data are being evaluated to determine whether primary NOx emissions are reduced
- National Governments (UK, Netherlands…) are researching this
  - Early evidence suggests that SCR-equipped engines may be challenged under light-load / urban operation
    - SCR at high load operation is highly effective, but less so at low speed/load
    - EGR solution for Euro V trucks most effective between 10kph and 60kph
    - However the TfL data shows that this is not necessarily the case for buses
- Data from TNO report MON-RPT-033-DTS-2009-03840 plotted overleaf, together with TfL data for buses (assuming average MLTB cycle speed of 14kph)
- A key conclusion from this work is that both Euro V technologies (SCR & EGR) may not behave effectively under real world conditions

On road measurement of Euro V trucks shows NOx emissions intensity in excess of levels predicted from legislative engine tests



- PEMS measurements of real-world NOx emissions for Euro V trucks
- NOx emissions from these trucks in common urban situations are up to ~3x higher than legislative predictions
- Only under high speed and corresponding high exhaust temperatures, do the NOx emissions match legislative predictions
- Whilst not directly comparable, the real world NOx intensity levels of the TfL Buses are also in excess of the levels predicted from legislative engine tests

TNO report | MON-RPT-033-DTS-2009-03840, TfL Hybrid & Conventional bus data

Contents

Air quality impacts of engine/vehicle technologies on Unregulated emissions

- Because unregulated emissions are by definition not often measured we have to rely on expert opinion to describe the expected impact of engine/vehicle technologies on unregulated emissions
- The following slides address selected unregulated emissions of significance for air quality

 © Ricardo plc 2013

Nitrogenous Species

- **Nitrous Oxide (N_2O) – A potent greenhouse gas**
  - Nitrous oxide has been observed as a noticeable emission from SCR systems, however early work has been from immaturely calibrated systems and future refinements may lead to SCR with near zero N_2O emissions.
  - From conventional vehicles with oxidation and three-way catalysts, emissions from lean burn types (Diesel and G-DI) are higher than from stoichiometric PFIs.
- **Nitrogen Dioxide (NO_2) – A respiratory irritant and contributor to acid rain and ozone formation**
  - Oxidation catalysts and catalysed DPFs increase NO_2 by the oxidation of nitric oxide on platinum. This coupled with the lean operation of Diesel engines means that conventional diesels, and those equipped with DPFs, are the highest emitters of $NO_{2.}$ Note that while NO_2 is unregulated, it is controlled within overall NOx.
- **Ammonia (NH_3) – Odorous and reactive**
  - Ammonia emissions may be significant from SCR systems if clean-up catalysts are not employed, but NH_3 can be efficiently controlled by downstream DOCs under hot operation.
  - Conventional SI engines including gas engines with TWCs preferentially produce ammonia under transient enrichment and cold starts. Emissions from these vehicle types are generally higher than from conventional diesels

Hydrocarbon species (1)

- **Methane (CH_4) – relatively low air quality impact but a potent greenhouse gas**
  - Methane is generally difficult to eliminate by catalysis except at high temperatures (>400ºC). During regulatory transient cycle tests the majority of methane emissions from all technologies are observed during cold start. Otherwise, highest methane emissions are observed from low average speed, mostly transient inner-city cycles, where catalyst temperatures remain consistently low throughout the entire test.
  - When technologies are compared highest emissions are observed from the vehicles and engines running on CNG.
  - For a gas engine, methane partially oxidises to formaldehyde, especially under cold start conditions. Oxidation can proceed to formic acid. Another partial oxidation product is CO. However these partial oxidation reactions are expected to be less prevalent in gas engines than diesel and methanol engines
  - DPF regeneration on diesels may increase CH_4 compared to non-DPF diesels by cracking post-injected fuel across the oxicat under certain conditions
  - Regulation of methane varies by engine type, emissions are regulated directly for dedicated CNG engines and as part of THC for Diesel engines at Euro VI in the EU
- **Benzene (C_6H_6) - toxic**
  - Benzene emissions are present in the engine-out emissions from both gasoline and Diesel vehicle types. Oxidation catalysts for diesels are likely to eliminate benzene.

Hydrocarbon species (2)

- **1,3-butadiene (C_4H_6)**
  - Emissions of 1,3-butadiene are wholly derived from combustion of the fuel: it is not present in unburned fuel. Emissions levels from conventional diesel engines are broadly similar to gasoline passenger cars, where episodes of fuel enrichment may lead to elevated 1,3-butadiene emissions particularly from gasoline-fuelled vehicles, but data are scarce in the literature so this cannot be confirmed. Unlikely to be an issue for gas engines
- **Carbonyl Species [R-(HC)=O, R-(RC)=O]**
  - Carbonyl species are favoured from stratified lean operating conditions where partial oxidation occurs and from cold start tests where catalytic control is poor and partial fuel oxidation high. Carbonyl production is also maximised from fuels containing suitable precursor compounds such as oxygenated species and stable molecules: methanol and ethanol are oxidised to formaldehyde and acetaldehyde respectively and toluene is oxidised to benzaldehyde.
  - Partial oxidation of methane (gas) fuel is possible leading to formaldehyde, which has been observed in the exhaust of large gas fuelled power generation engines

Sulphur Species

- **Hydrogen Sulphide (H_2S) and Sulphur Dioxide (SO_2)**
  - Emissions of H_2S and SO_2 from TWCs are related to the sulphur level in the fuel (and as this is reduced by legislation , the lubricant) and the instantaneous AFR. Fuel sulphur progressively poisons active sites on the catalyst surface, but this sulphur can be released.
  - Transient lean operation will lead to oxidising conditions and the emission of SO_2, while rich operation will lead to emissions of H_2S.
  - SO_2 emissions are highest from conventional diesels running on high sulphur fuel, due to the continuous lean operation. H_2S emissions from modern engine technologies have been observed from both conventional diesel and gasoline light-duty vehicles, but at relatively low levels (<0.1mg/km).
  - If fuel and lube oil sulphur is kept under control sulphur species emissions should be minimal

Contents

Conclusions

- At Euro VI and EPA10 emissions levels, diesel and gas engine emissions should be broadly indistinguishable within measurement error, emissions from both engine types will be very low
- Depending on the specific legislation regimes, some types of engine are permitted to emit excessive emissions of certain species:
  - E.g. HPDI engine certified to USA EPA10 diesel regulations requires no methane control
  - Improved legislation is anticipated (e.g. proposed UN ECE regulation for dual fuel engines)
- Technologies such as hybridisation that may be applied to vehicles to reduce the amount of fuel burned (improve fuel efficiency, reduce CO_2) **should** have a corresponding effect on air quality emissions
  - However vehicle test data indicates that both hybrid buses and conventional buses and trucks in operation exceed modelled emissions levels
  - In some cases the hybrid buses emit more per unit of fuel burned than conventional buses – indicating further opportunity to optimise emissions control around the operating cycle
  - Consideration of hybrid technologies in the legislative test cycle is needed to facilitate further air quality reduction
- Technologies which impact the duty cycle of the engine for a given route (e.g. hybrids) can have complex impacts on aftertreatment and EGR behaviour. This should be assessed for each vehicle configuration at the powertrain integration stage.
- Unregulated emissions remain a concern to legislators and are likely to become regulated over time where they are seen to have AQ impact. Unregulated emissions of current concern are:
  - From diesels: ammonia, N_2O/NO_2, aldehydes, benzene
  - From gas engines: methane, ammonia (if SCR used), aldehydes

© Ricardo plc 2013