Preparing a low CO_2 technology roadmap for buses

Final Report – updated 3 July 2013

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Task	**Q003889**
Confidential	**LowCVP**
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Approved	**Dave Greenwood** **Hybrid & Electric Systems Product Group Head**

Executive summary

- The purpose of this study was to identify the low carbon technologies for UK urban buses that could achieve >2% GHG savings, and to develop a technology roadmap to illustrate when these technologies are likely to be deployed into the bus market
- Specifically the study addressed the following questions:
  - Which low carbon technologies are suitable for buses and have the potential to achieve CO_2 savings greater than 2% compared with a comparative diesel bus? For which technologies is the return on investment sufficiently quick for the low carbon technology to be commercially viable?
  - How are these technologies likely to be grouped into packages for deployment in buses? What is the combined CO_2 emissions and fuel savings for each technology package?
  - Which of these technologies for buses are likely to be strategically important for the rest of the heavy commercial vehicle market in contributing to CO_2 emissions reduction?
  - What is the low carbon technology roadmap for buses in the timescales 2012-2020 and 2020-2050?

Costs and benefits were identified for technologies expected to give > 2% GHG reduction for UK urban buses

Technology description	**Technology price (£)***		**Maintenance cost (£ per year)**		**TTW CO_2 benefit (% change)**		**WTW CO_2 benefit (% change)**	
Single/Double Deck	SD	DD	SD	DD	SD	DD	SD	DD
Lightweighting step 1	6000	10000	-	-	3	3	3	3
Lightweighting step 2	18000	25000	-	-	7	8	7	8
Smart alternator	600	600	-	-	5	5	5	5
Smart compressor	500	500	-	-	6	6	6	6
Rankine cycle heat recovery (exhaust)	9000	12000	-	-	3	4	3	4
Rankine cycle heat recovery (coolant)	9000	12000	-	-	3	3	3	3
IVT	15000	15000	-	-	15	15	15	15
Stop/start system	1400	1400	-500	-500	9	9	9	9
Mild hybrid system	6000	6400	60	60	13	13	13	13
Full hybrid – parallel (incl battery replacement)	90000	105000	-3273	-3940	35	35	35	35
Full hybrid – series (incl battery replacement)	75000	90000	-3940	-4607	40	40	40	40
Full hybrid – parallel hydraulic	37500	37500	60	60	20	20	20	20
Full hybrid – series hydraulic	37500	37500	60	60	35	35	35	35
Flywheel energy storage	15000	15000	60	60	17	17	17	17
Pneumatic booster system	600	600	-	-	3	3	3	3
Battery Electric Vehicle (incl battery replace.)	97500	105000	-4940	-6607	100	100	30	30
Trolley bus	300000	500000	-	-	100	100	24	24

*Trolley bus price does not include infrastructure cost

Price not including subsidies ^ Positive figure indicates better/less than baseline diesel, negative worse/more

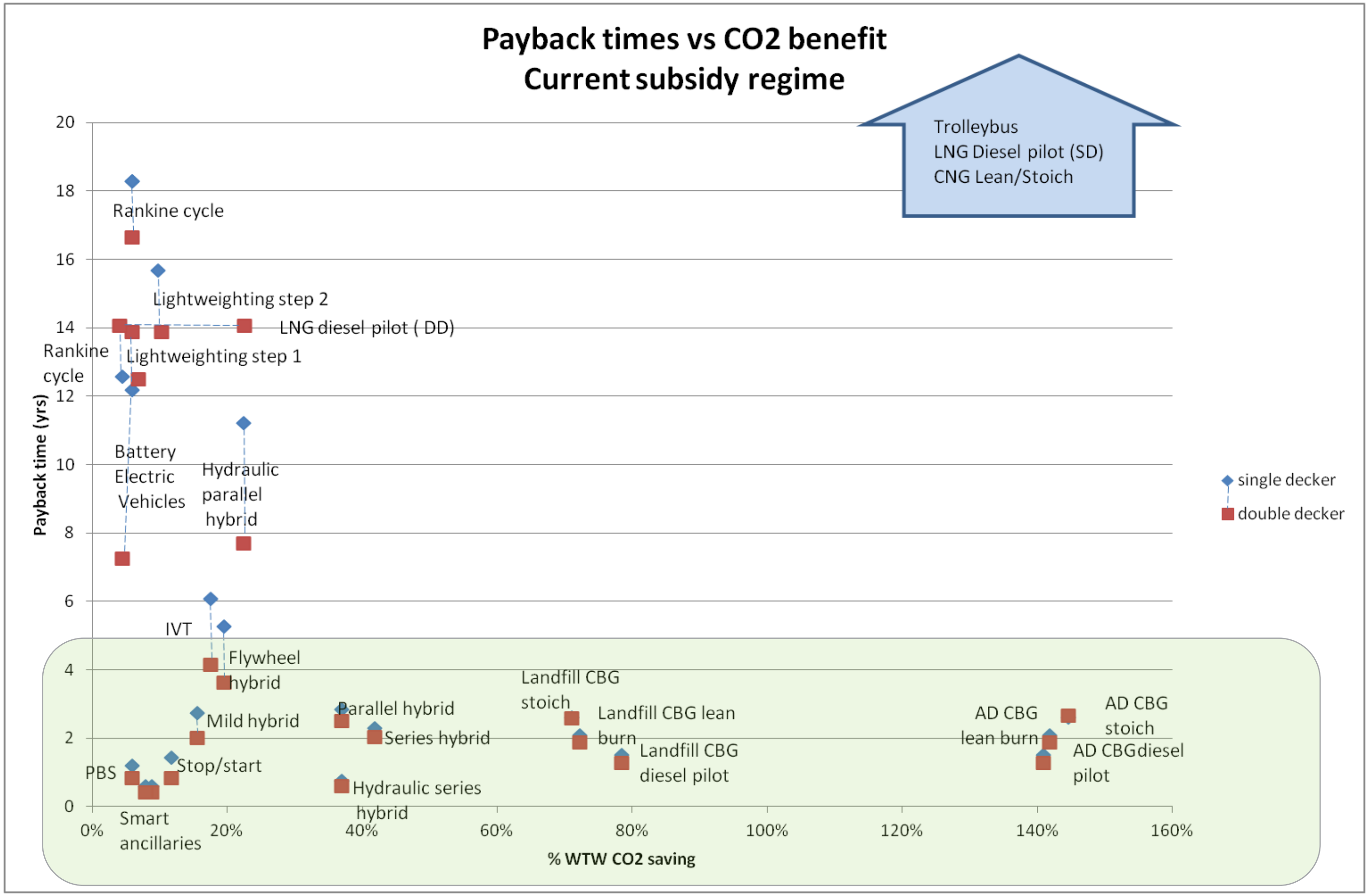
WTW benefits of alternative fuels were reviewed, including consideration of UK CNG pathways

Technology description	Technology price (£)*		Maintenance cost (£ per year)		TTW CO_2 benefit (% change)^		WTW CO_2 benefit (% change)^	
Single/Double Deck	SD	DD	SD	DD	SD	DD	SD	DD
CNG in stoich (range of UK pathways)	45000	45000	-500	-500	-4	-4	+5 to -16	+5 to -16
CNG in Lean Burn (range of UK pathways)	45000	45000	-500	-500	1	1	+10 to -11	+10 to -11
LNG in Diesel Pilot (range of UK pathways)	45000	45000	-500	-500	15	15	+23 to +4	+23 to +4
AD biomethane in Stoich	9000	9000	-500	-500	-4	-4	146	146
AD biomethane in Lean Burn	9000	9000	-500	-500	1	1	143	143
AD biomethane in Diesel Pilot	9000	9000	-500	-500	15	15	142	142
Landfill Liquefied biomethane in Stoich	9000	9000	-500	-500	-4	-4	70	70
Landfill Liquefied biomethane in Lean Burn	9000	9000	-500	-500	1	1	71	71
Landfill Liquefied biomethane in Diesel Pilot	9000	9000	-500	-500	15	15	78	78
Bioethanol E95 in CI engine (5% ignition enhancer)	21000	32000	-	-	2	2	68	68
Hydrogen FC (Industrially sourced H_2)	600000	700000	-10000	-10000	100	100	17	17
Hydrogen FC (renewable H_2)	600000	700000	-10000	-10000	100	100	75 to 94	75 to 94
Hydrogen ICE (Industrially sourced H_2)	45000	45000	-	-	100	100	-15	-15
Hydrogen ICE (renewable H_2)	45000	45000	-	-	100	100	66 to 92	66 to 92
Bio Dimethyl Ether (DME)	22500	22500	-	-	6	6	104	104
BTL	-	-	-	-	0	0	92	92
HVO	-	-	-	-	0	0	60	60

* Price not including subsidies ^ Positive figure indicates better/less than baseline diesel, negative worse/more

Payback times were assessed, based on assumptions about bus operations and fuel prices, under the current subsidy regime..

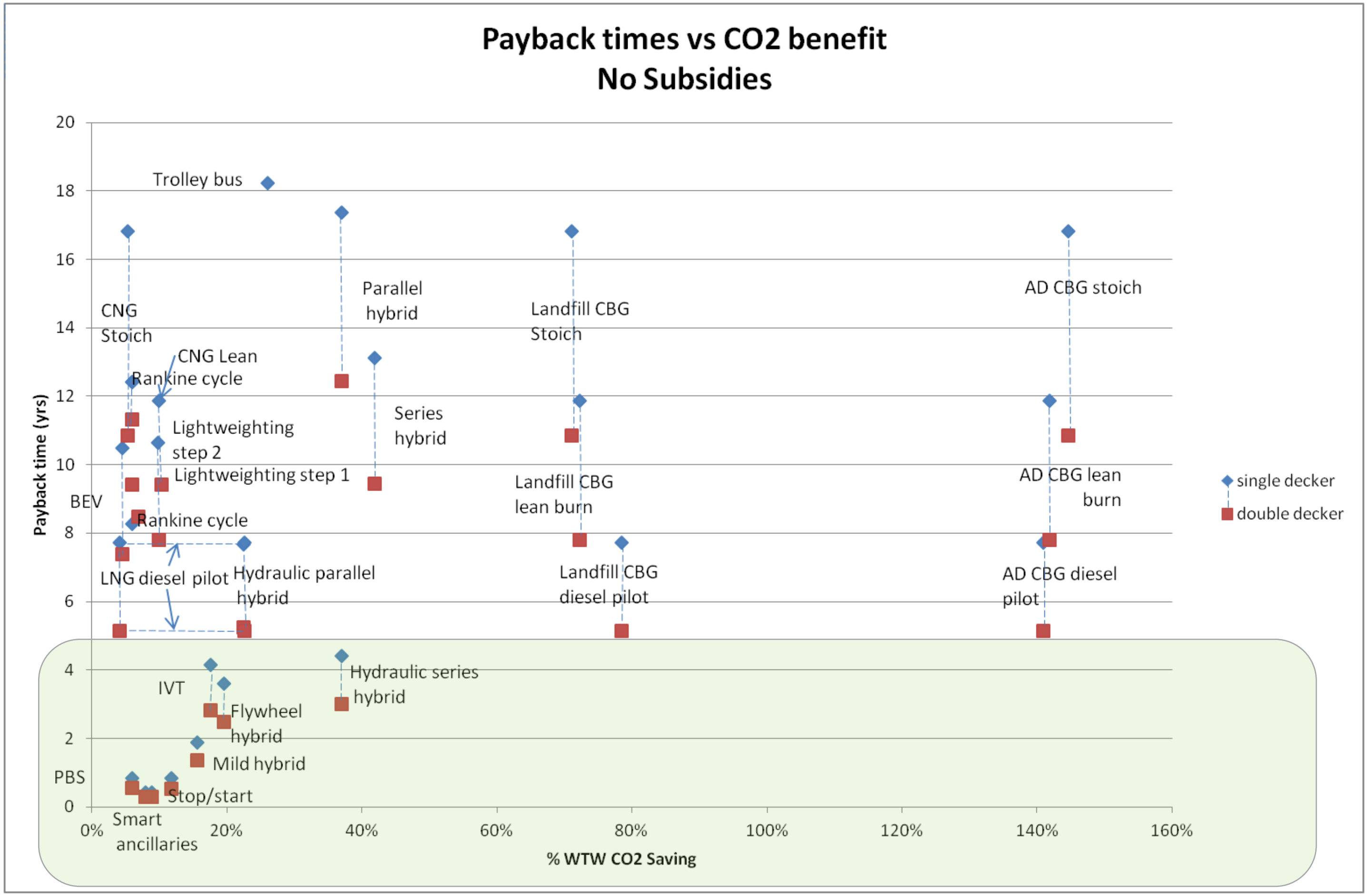
- Highlighted area shows payback time < 5 yrs
- The following technologies lie in this zone, given the study assumptions:
  - Biomethane powered engines, stop start, PBS, smart ancillaries, mild hybrid, flywheel hybrid, parallel and series battery hybrids, series hydraulic hybrid, IVT
- BSOG increases payback times due to lower effective fuel cost



Assumptions: 40000 miles pa both SD and DD; fuel consumption 8mpg SD, 6mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh.

..and with no subsidies – UK subsidies were found to have a significant and complex effect on commercial viability

- With no subsidies, full battery hybrid and gas powered technologies have payback times of greater than 5 years
  - Series hydraulic hybrid, mild hybrid and flywheel hybrid technologies still have payback times less than 5 years
- Measures to reduce ancillary power use, stop start, IVT and pneumatic booster systems also payback in less than 5 years
- Note that reducing subsidies also increases operating costs for a standard diesel bus



Assumptions: 40000 miles pa both SD and DD; fuel consumption 8mpg SD, 6mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh.

Technology packages have been selected to give a range of benefits and technology prices

- Selected technology packages and their benefits are shown in the table below
  - Payback times are shown without subsidies

Package number	Description	Technology price (£)		WTW CO_2 benefit (%)		Payback time (years)	
		SD	DD	SD	DD	SD	SS
1	Stop start, PBS and smart ancillaries	3000	3000	18	18	0.3	0.2
2	Mild hybrid and smart ancillaries	7100	7500	22	22	0.7	0.5
3	Flywheel hybrid and stop start	16400	16400	24	24	1.5	1.0
4	Series hybrid with diesel pilot biomethane engine	120000	135000	125	125	9.8	7.0

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12.

The suitability of selected technologies for other commercial vehicle applications was assessed

- Technologies identified for buses with applicability in other sectors
  - Technologies with applicability across most sectors are highlighted

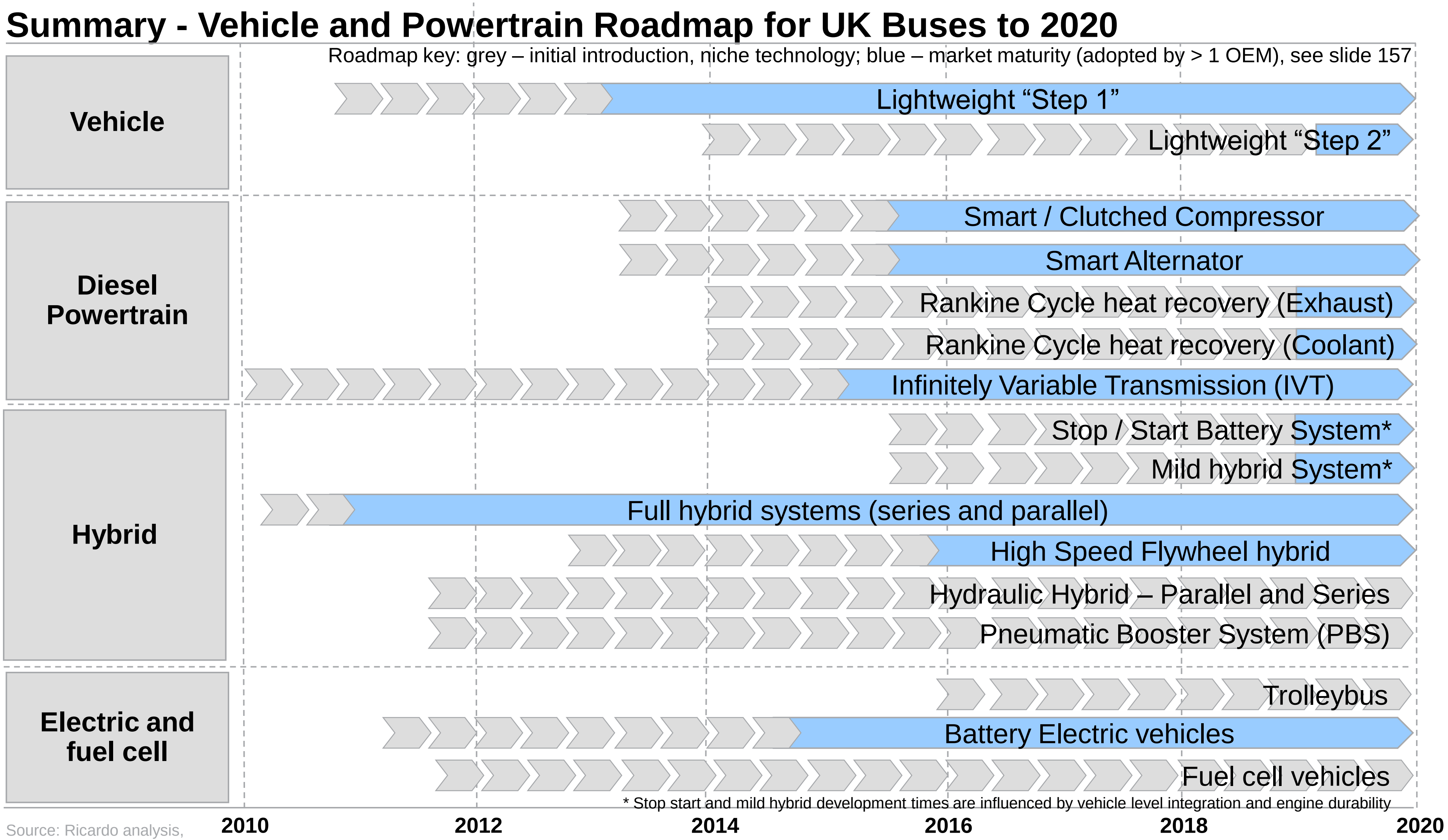
Technology	**Vehicle suitability**					
	Bus	Coach (Intercity)	Heavy Duty Truck (Intercity)	Medium Duty Truck (Delivery)	Utility Truck (Powered body)	Off Highway (Tractor, excavator)
Lightweighting	Yes	Yes	Yes	Yes	Yes	No (often ballasted for stability)
Smart ancillaries	Yes	Yes	Yes	Yes	Yes	Possibly
Rankine EHR	Poor cost benefit	Yes	Yes	Poor cost benefit	Poor cost benefit	No
IVT	Yes	Unlikely due to constant speed operation		Possibly	Possibly	No
Stop start/mild hybrid	Yes	Unlikely due to constant speed operation		Yes	No	No
Full hybrid	Yes	Unlikely due to constant speed operation		Yes	Yes	Yes
Flywheel	Yes	Unlikely due to constant speed operation		Yes	Possibly	Yes
Pneumatic booster	Yes	Yes	Yes	Yes	Yes	Yes

Technologies with a range of potential applications could achieve economies of scale or synergies with other sectors

- Technologies identified for buses with applicability in other sectors
  - Technologies with applicability across most sectors are highlighted

Technology	Vehicle suitability					
	Bus	Coach (Intercity)	Heavy Duty Truck (Intercity)	Medium Duty Truck (Delivery)	Utility Truck (Powered body)	Off Highway (Tractor, excavator)
BEV	Yes	No	No	Yes	Possibly (small vehicles)	No
Trolley bus	Yes	No	No	No	No	No
CNG Stoich/lean	Yes	Yes	Yes	Yes	Yes	Possibly
LNG diesel pilot	Possibly (niche)	Possibly (niche)	Yes	Possibly (niche)	Possibly (niche)	No
Biomethane	Yes	Yes	Yes	Yes	Yes	Possibly
E95/Bio DME	Yes (niche)	Possibly (niche)	Possibly (niche)	Possibly (niche)	Possibly (niche)	Possibly (niche)
Hydrogen FC/ICE	Yes (niche)	Possibly (niche)	Unlikely	Possibly (niche)	Possibly (niche)	Unlikely
BTL/HVO	Yes	Yes	Yes	Yes	Yes	Yes

Many low carbon technologies require development for bus application



Summary - Vehicle and Powertrain Roadmap for UK Buses to 2020

Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

Vehicle
- Lightweight “Step 1”
- Lightweight “Step 2”

Diesel Powertrain
- Smart / Clutched Compressor
- Smart Alternator
- Rankine Cycle heat recovery (Exhaust)
- Rankine Cycle heat recovery (Coolant)
- Infinitely Variable Transmission (IVT)

Hybrid
- Stop / Start Battery System*
- Mild hybrid System*
- Full hybrid systems (series and parallel)
- High Speed Flywheel hybrid
- Hydraulic Hybrid – Parallel and Series
- Pneumatic Booster System (PBS)

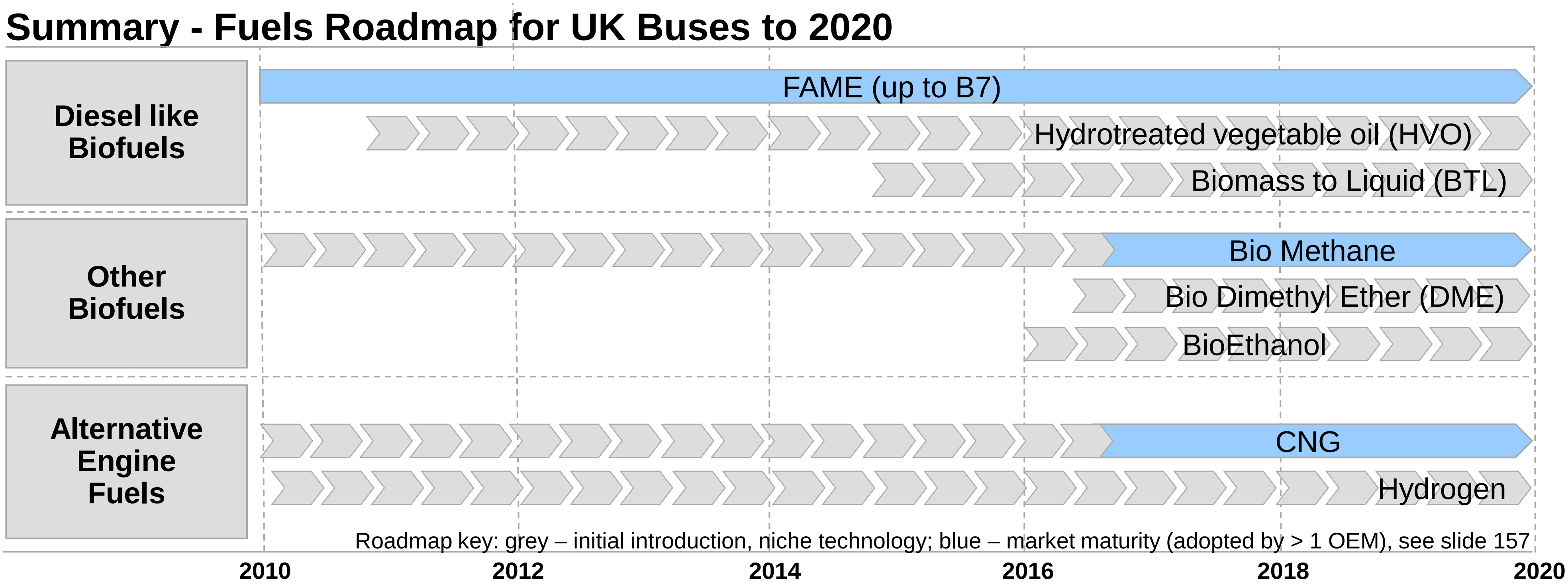
Electric and fuel cell
- Trolleybus
- Battery Electric vehicles
- Fuel cell vehicles

* Stop start and mild hybrid development times are influenced by vehicle level integration and engine durability

Source: Ricardo analysis,

While many biofuel and alternative options exist for buses, only CNG or biomethane have the potential for mass market penetration in the near term

Summary - Fuels Roadmap for UK Buses to 2020

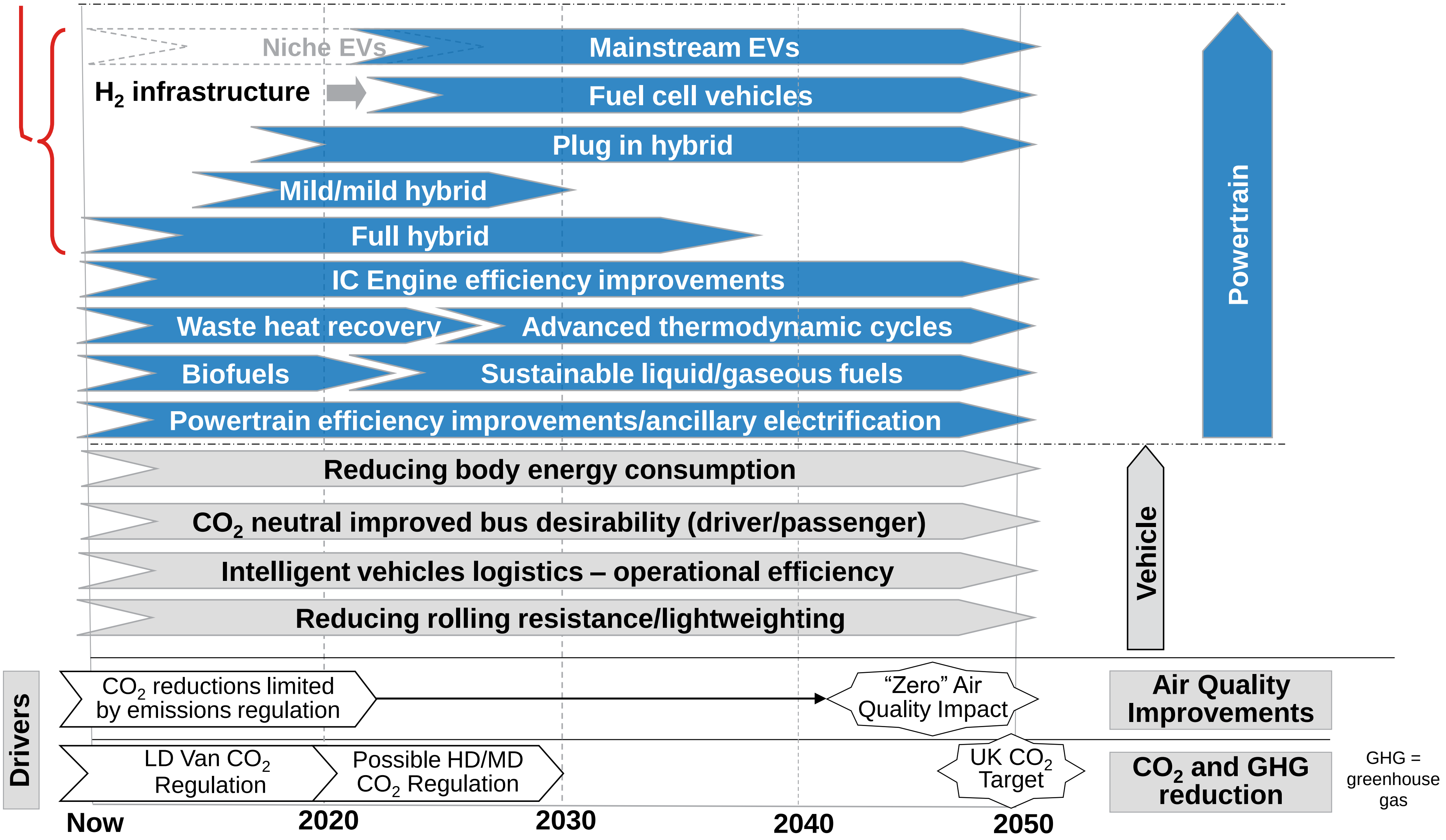


Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

Source: Ricardo analysis,

Meeting long term CO_2 targets requires the development of advanced technologies, in parallel with improvements to ICEs

Breakthrough in energy storage



Niche EVs

Mainstream EVs

H_2 infrastructure

Fuel cell vehicles

Plug in hybrid

Mild/mild hybrid

Full hybrid

IC Engine efficiency improvements

Waste heat recovery

Advanced thermodynamic cycles

Biofuels

Sustainable liquid/gaseous fuels

Powertrain efficiency improvements/ancillary electrification

Powertrain

Reducing body energy consumption

CO_2 neutral improved bus desirability (driver/passenger)

Intelligent vehicles logistics – operational efficiency

Reducing rolling resistance/lightweighting

Vehicle

Drivers

CO_2 reductions limited by emissions regulation

"Zero" Air Quality Impact

Air Quality Improvements

LD Van CO_2 Regulation

Possible HD/MD CO_2 Regulation

UK CO_2 Target

CO_2 and GHG reduction

GHG = greenhouse gas

Now

2020

2030

2040

2050

Conclusions (1/2)

- Technologies were selected for inclusion in this study where they were expected to give > 2% CO_2 benefit for UK single and double deck urban buses, selected technologies are shown below:
  - Vehicle and powertrain technologies: Lightweighting, smart clutched compressor, smart alternator, Rankine cycle, IVT, stop start, mild hybrid, series and parallel electric and hydraulic hybrids
  - Fuels: Compressed natural gas (CNG or LNG), compressed biomethane, HVO, BTL, Hydrogen (Internal combustion engines and fuel cell), electricity
- Analysis of WTW CO_2 emissions for each technology was carried out
  - Biomethane is expected to give significant WTW CO_2 reductions for bus application, however expected UK pathways do not match those examined in the literature
  - WTW CO_2 benefits for fossil CNG technologies vary from an increase compared to Diesel to a significant benefit depending on engine technology and gas pathway
  - Detailed independent analysis of the WTT CO_2 emissions for UK developing biomethane and fossil CNG pathways is recommended
- Payback time was estimated for these technologies for single and double deck vehicles, both with and without UK bus subsidies
  - Under the current subsidy regime, hybrid and biomethane powered vehicles are expected to have a payback time less than 5 years
    - If no fuel or capital subsidies were available, payback times for most hybrid and gas powered technologies are likely to be greater than 5 years
  - Technologies that were expected to have a payback time of less than 5 years without support were mild hybrid, flywheel hybrid, IVT, hydraulic series hybrid, PBS and smart ancillaries

Conclusions (2/2)

- Technology packages were then generated to give a range of benefits for UK buses
  - Selected packages were: stop start with smart ancillaries; mild hybrid with smart ancillaries; flywheel hybrid with stop start; full series hybrid with biomethane fuelled engine
- The suitability of the selected technologies for other commercial vehicle sectors was examined to identify areas where economies of scale or other synergies may be achieved
  - Lightweighting, smart ancillaries, full hybrid, flywheel hybrid, pneumatic booster, biomethane/CNG and substitutional biofuels are expected to be applicable across a range of commercial vehicle sectors
- The major benefits currently being sought for the commercial vehicle industry however are not likely to give the most significant CO_2 benefits for the bus industry
    - Therefore specific action may be required to pull through bus specific technologies
- Roadmaps were then developed for UK buses for both the long and short term (up to 2020)
  - Short term roadmapping showed that many low carbon technologies require development for bus application
    - In the near term, while many biofuel and alternative fuel options exist for buses, only CNG or biomethane have the potential for mass market penetration
  - In the longer term, the development of advanced technologies for buses is needed, in parallel with improvements to ICEs, to meet long term CO_2 targets

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Introduction

- The Low Carbon Vehicle Partnership issued an invitation to tender for a study entitled “Preparing a low CO_2 technology roadmap for buses”
- Current incentives for low carbon emission buses in the UK are based on the bus achieving at least 30% less GHG emissions than an average Euro 3 diesel bus
- Hybrid and electric buses are currently not commercially viable without Government support
- There could be low carbon technologies that are cheaper to implement, but which don’t achieve a 30% reduction in GHG emissions and therefore do not qualify for the incentives
- LowCVP want to understand the range of low carbon technology options for buses, and the wider role of these technologies could have in reducing GHG emissions for heavy goods vehicles
- The purpose of this study is to identify the low carbon technologies for buses that could achieve >2% GHG savings, and to develop a technology roadmap to illustrate when these technologies are likely to be deployed into the bus market

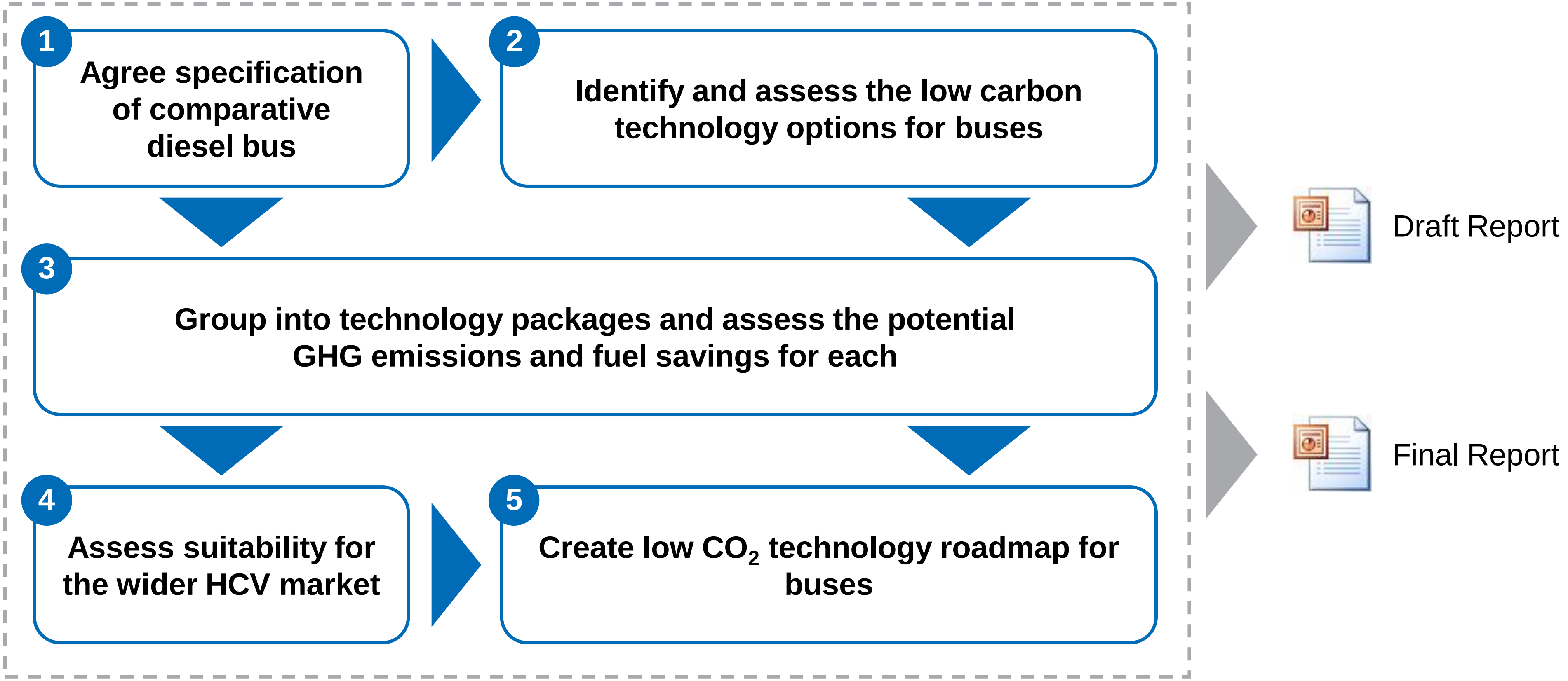
Source: LowCVP document “Preparing for a low CO_2 technology roadmap for buses – Invitation to Tender”, received by email from Gloria Esposito on Monday 27 February 2012

Project Objectives

This study aims to answer these questions

1. Which low carbon technologies are suitable for buses and have the potential to achieve CO_2 savings greater than 2% compared with a comparative diesel bus? For which technologies is the return on investment sufficiently quick for the low carbon technology to be commercially viable?
2. How are these technologies likely to be grouped into packages for deployment in buses? What is the combined CO_2 emissions and fuel savings for each technology package?
3. Which of these technologies for buses are likely to be strategically important for the rest of the heavy commercial vehicle market in contributing to CO_2 emissions reduction?
4. What is the low carbon technology roadmap for buses in the timescales 2012-2020 and 2020-2050?

The project methodology is based on a set of tasks designed to answer the questions set out by the objectives



1 **Agree specification of comparative diesel bus**

2 **Identify and assess the low carbon technology options for buses**

3 **Group into technology packages and assess the potential GHG emissions and fuel savings for each**

4 **Assess suitability for the wider HCV market**

5 **Create low CO_2 technology roadmap for buses**

Draft Report

Final Report

The study draws on technical, market and public domain information, supplemented by the experience of Ricardo experts

- The study was conducted using a combination of Ricardo expert input and public domain information
- Public domain information utilised included, but was not limited to:
  - OEM technical specifications and press releases
  - Technical papers
  - Manufacturers material (e.g. websites, brochures)
  - Trade press articles
  - Industry associations, for example SMMT, ACEA
  - Industry bodies, for example, Freight Best Practice, Renewable Fuels Agency
  - Ricardo PowerLink database
- Where used, these sources are cited on each slide
- Ricardo has applied its own expertise and engineering judgement to assess the validity of publicly made claims, and where necessary provide a balanced summary of the claimed benefits of different technologies, where conflicting or variable data exists
- In these cases, this is identified on each slide as “Ricardo analysis”, and this usually relates to analysis of the detailed sources cited on the slides which immediately follow
- Where appropriate Ricardo has included the findings of its own original research and analysis, this is identified as “Ricardo research”

The effect of low carbon technologies and fuels on both Well to Wheels and Tank to Wheels CO_2 emissions is considered

- Tanks to Wheels (TTW) or tailpipe CO_2 (usually g/km) refers to CO_2 emissions directly from the vehicle as a result of combustion of fuel
- Well-to-wheel (WTW) CO_2 emissions (quoted in a variety of units) of a particular activity captures the CO_2 emitted during fuel/electricity production, distribution and vehicle use
- Well to Tank (WTT) CO_2 emissions refer to the CO_2 emitted during fuel/electricity production and distribution
- CO_2 (carbon dioxide) emissions are the primary focus of this report
  - CO_2 is the most common greenhouse gas, although it does not have the highest global warming potential on a mass basis
- Other vehicle emissions have global warming potential
  - For example the global warming potential of methane is 23 times higher than CO_2 ,Nitrous oxide (NOx) has 310 times the global warming potential of CO_2 when considered on a mass basis over a 100 year time horizon
  - Where all vehicle emissions that have global warming potential are considered, the term greenhouse gas emissions (GHG) is used
- CO_2 reduction analysis is included on a TTW basis for vehicle and powertrain technologies – and a WTT and TTW basis for alternative fuelling technologies
  - TTW CO_2 emissions are assumed to consist only of CO_2
  - On a WTT basis overall greenhouse gas emissions are considered – and reported on a CO_2 equivalent basis
- Fuel consumption (eg litres/100km) and CO_2 emissions are directly proportional for a given fuel, whereas fuel economy (eg mpg) and CO_2 emissions are inversely proportional
  - Fuels with different carbon content (i.e. chemically different composition) have different correlation gradients

Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c)

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The potential for a technology to reduce CO_2 emissions is assessed compared to a baseline single and double deck bus

- Baseline bus specifications were developed from manufacturers specifications for the four best selling single and double deck buses in 2011 and agreed with the LowCVP bus working group at a project meeting on 22 June 2012
- The baseline fuel is assumed to be current UK pump specification, i.e. EN590 containing 5% biodiesel

	Single Deck Bus	Double Deck Bus
Capacity (seats/standees)	38/24	63/27
Length (m)	9.7	11.0
GVW (t)	12	18
Tare weight (t)	8.1	12.6
Power (kW) / Speed (rpm)	117 @ 2500	186 @ 2300
Torque (Nm) / Speed (rpm)	600 @ 1100 – 1600	1020 @ 1200-1600
Emissions Level	Euro V / EEV	Euro V / EEV
Emissions Reduction Technology	SCR	SCR
Engine Displacement (l)	4.5	6.7
Transmission Type	Torque converter automatic	Torque converter automatic
Transmission Ratios	5	6

Source: SMMT bus sales data, OEM specifications, Ricardo analysis

Assessment of the return on investment for each technology is calculated based on a set of assumptions about bus operations

- **The focus for the study is on UK buses operating over an urban cycle**
- Assumptions were agreed with LowCVP Bus Working Group at a project meeting on 22 June 2012
- **Annual mileage** is based on the recommendation of the LowCVP Bus Working Group for buses covering an urban duty cycle
- **Fuel consumption** is based on road test fuel consumption data from public domain sources combined with recommendations from the LowCVP Bus Working Group
- **Fuel price** - a constant fuel price is assumed, based on expected fleet fuel prices in 2012, excluding VAT, fuel duty and BSOG (detailed on the next slide)
- **Technology price** – based on the additional bill of materials cost of a complete system with a markup of 100% to provide an estimate for vehicle price increase **(not including, for example, additional costs for operators such as infrastructure or capital financing)**
- **Maintenance costs** – An estimate for the change in annual maintenance costs compared to a baseline bus is included in calculations of return on investment where the technology has a direct effect on these costs

	Single Deck Bus	Double Deck Bus
Annual mileage (miles)	40,000	40,000
Fuel consumption (mpg)	8	6

Source: Ricardo analysis, LowCVP bus working group, Autobus, Route 1, Bus and Coach Buyer

Fuel prices assumed in this study are based on 2012 prices

- Fuel price paid by operators is a combination of base fuel price, fuel duty and BSOG
  - Base fuel prices are based on public domain information
  - Duty and BSOG values are as applicable on 1 September 2012
- An additional fuel subsidy is available within BSOG for low carbon buses
  - 6p per km is available for buses that give a 30% reduction in GHG emissions

	Base price	Fuel duty	BSOG	Price with BSOG	Price without BSOG
Diesel fuel price (pence per litre)	50	57.95	34.57	73.4	107.95
Bioethanol (pence per litre)	50	57.95	34.57	73.4	107.95
CNG fuel price (pence per kg)	60.3	24.70	18.88	66.12	85.0
CBG fuel price (pence per kg)	60.3	24.70	18.88	66.12	85.0
Electricity price (pence per kWh)	8.5	NA	NA	NA	NA
Hydrogen (pence per kg)	1000 - green, 2000 - industrial	NA	NA	NA	NA

Source: DfT, Go Ahead annual reports, Ricardo Analysis,

Contents

A long list of low carbon technologies was reviewed for application for buses, grouped into vehicle, powertrain and fuel themes

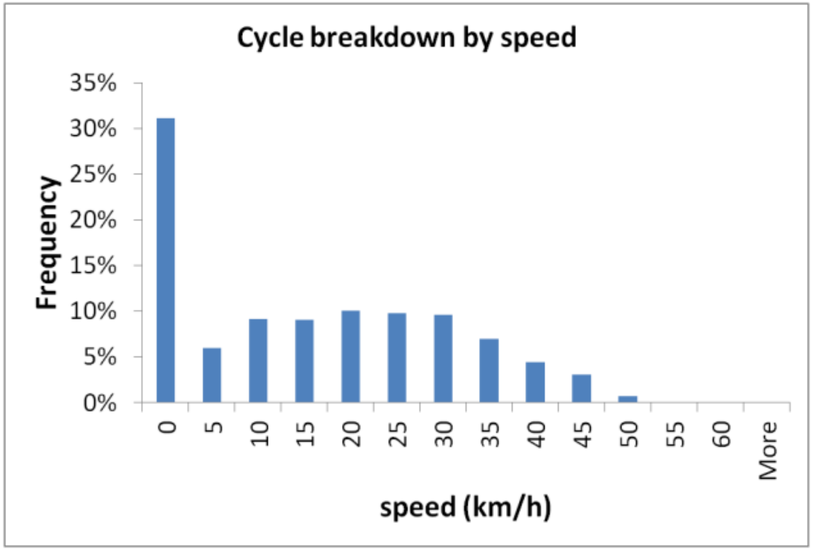
Technologies

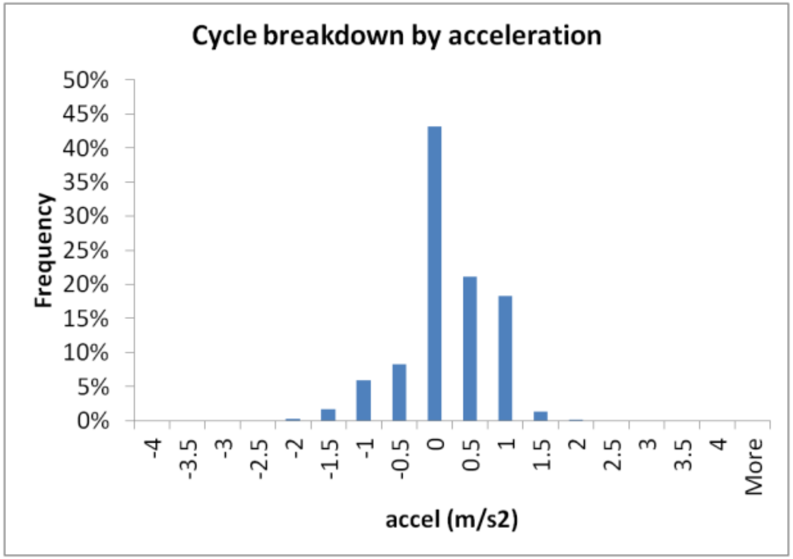
Vehicle	- Low carbon technologies that affect the whole vehicle - Reducing vehicle drag: Low rolling resistance tyres, aerodynamic body modifications - Lightweighting - Predictive cruise control, platooning and driver behaviour
Powertrain	- Low carbon technologies focused on engine, transmission and hybrid technologies - Engine enhancements: Combustion system and gas exchange system improvements, engine downsizing, engine friction reduction and lubricants, fuel additives, - Parasitic loss reduction: variable flow oil and water pump, clutched compressor, smart clutched compressor, smart alternator, EPAS, variable speed fans - Waste heat recovery/thermal management: Mechanical and electrical turbocompound, rankine cycle, thermoelectric generators, Heat to cool system (powers aircon from bus engine heat), stirling engine - Driveline: Automated manual transmissions, CVT, Eco-roll freewheel - Hybridisation: stop start, mild hybrid, series and parallel electric and hydraulic hybrids
Fuel	- Alternative fuels used to propel the vehicle - Fossil fuels: Compressed natural gas (CNG), LPG, GTL, CTL - Biofuels: Compressed biomethane, FAME, HVO, BTL - Other fuels: Hydrogen (Internal combustion engines and fuel cell), electricity

Technologies are included in the study where they are expected to give greater than 2% reduction in CO_2 emissions

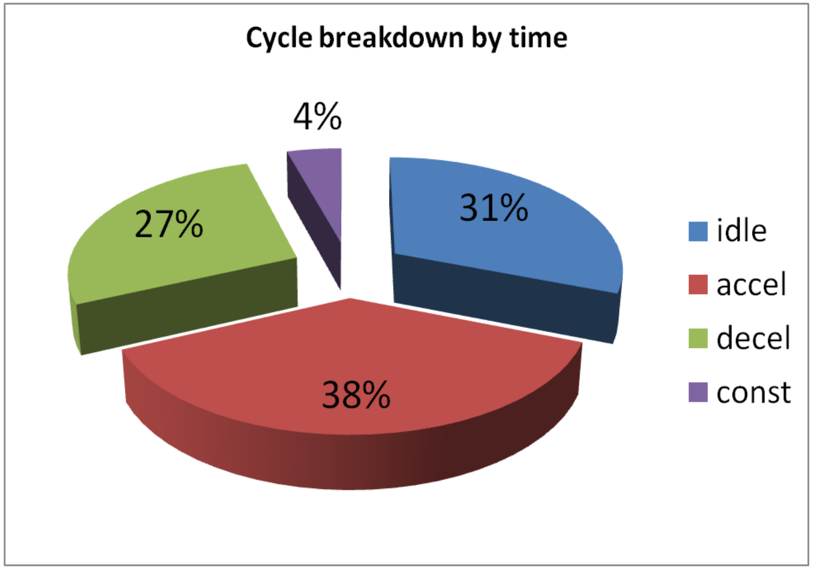
- CO_2 reduction potential for each of the technologies was examined for the baseline single and double deck vehicles over the Millbrook London Transport Bus drive cycle
  - This cycle was selected as is was considered to be representative of typical UK urban operation
- A combination of evidence from the public domain and Ricardo expert experience was used to assess the CO_2 reduction potential for each technology
- CO_2 reduction analysis is included on a TTW basis for vehicle and powertrain technologies – and a WTT and TTW basis for alternative fuelling technologies
  - TTW CO_2 emissions are assumed to consist only of CO_2
  - On a WTT basis overall greenhouse gas emissions are considered – and reported on a CO_2 equivalent basis
- **CO_2 reduction figures should be considered as indicative of the potential reductions, and should not be considered to offer proof of the effectiveness of the technologies**
- While CO_2 reductions are estimated over the MLTB cycle, in operation these reductions will vary due to factors such as route and driver behaviour
- Technologies are only considered for inclusion in the study where their application does not affect compliance with current Euro V emissions legislation
- Technologies which were excluded from the study are listed at the end of this section, together with brief commentary of the reasons they were excluded

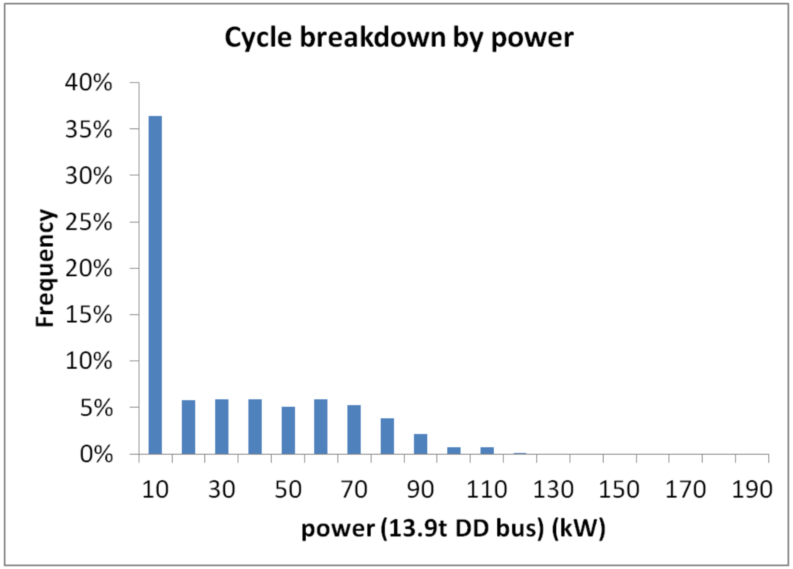
CO_2 reduction for low carbon technologies is highly dependent on drive cycle - MLTB cycle characteristics are shown below



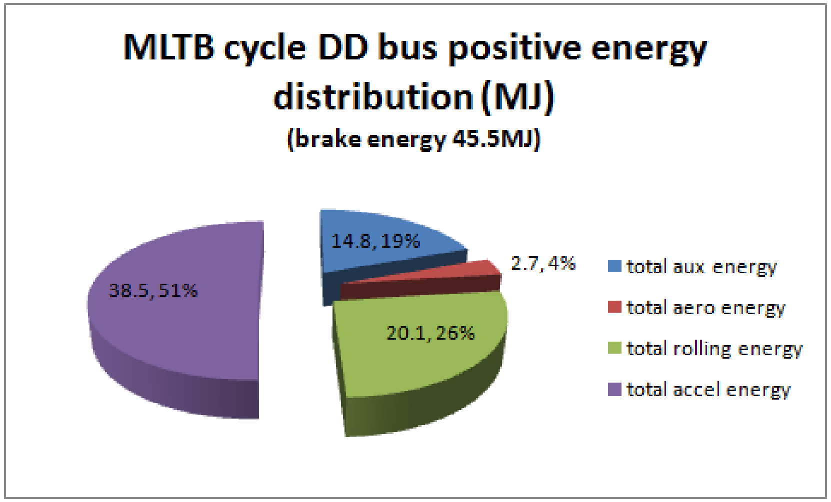


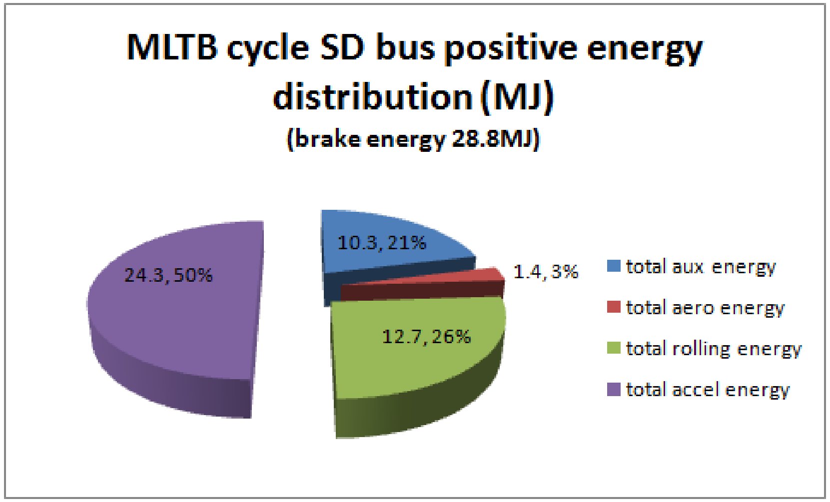
More detailed MLTB cycle statistics are shown in Appendix 1





Analysis of energy utilisation over the drive cycle informs Ricardo assessment of potential CO_2 reduction


MLTB cycle DD bus positive energy distribution (MJ)
(brake energy 45.5MJ)


MLTB cycle SD bus positive energy distribution (MJ)
(brake energy 28.8MJ)

- The distribution of positive energy (i.e. excluding energy dissipated in decelerating the vehicle) is shown above MLTB cycle for the baseline single and double deck buses (DD & SD). This analysis has been used extensively in the assessment of powertrain technologies
- Energy to accelerate the bus dominates (48-51%) and is less than the brake energy
  - Technologies to recover braking energy, such as hybrid technologies, would be expected to give significant CO_2 benefit. The proportion of energy used in accelerating the vehicle is used to cross-check hybrid claims
- Rolling resistance energy (dependent on weight, rolling resistance coefficient & speed) and auxiliary energy consumption (from alternator and compressor) are significant (26-29% and 14-21% respectively)
  - Technologies to reduce energy consumption by auxiliaries and reduce rolling resistance are expected to give noticeable CO_2 benefit. Auxiliary energy proportion is used to cross-check smart ancillary claims
- Aerodynamic energy in all cases is minimal (3-7%) due to the relatively low speed
  - Technologies to reduce aerodynamic drag are expected to have negligible effect on CO_2 emissions

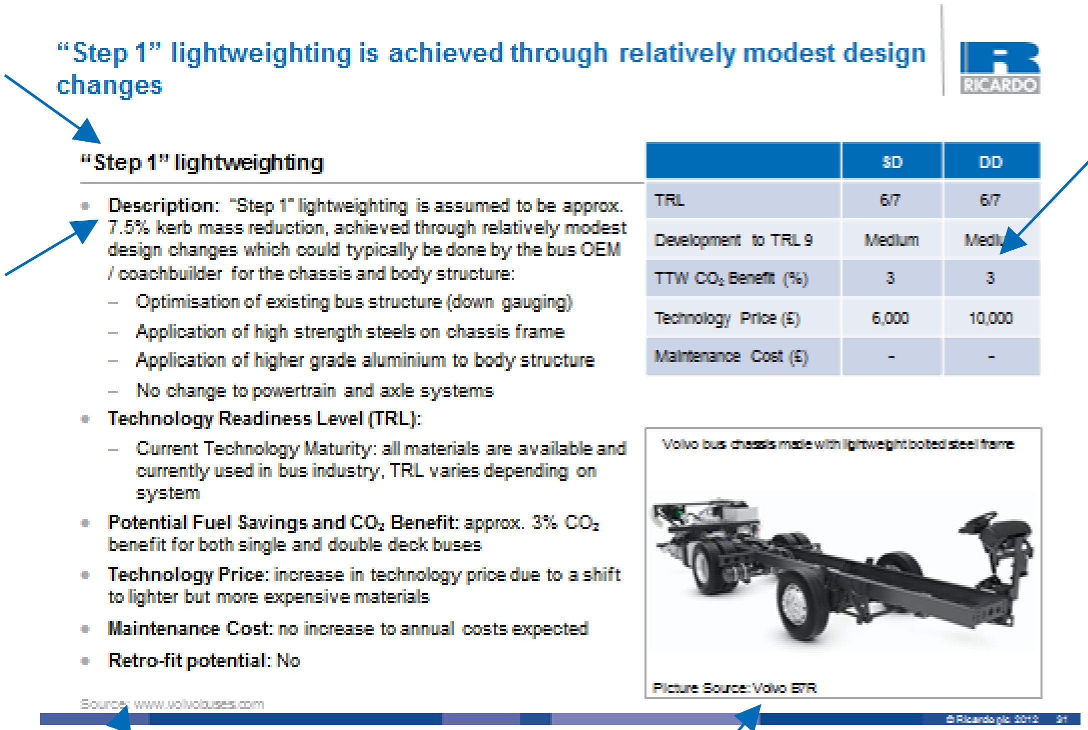
High level summaries are included for technologies that are expected to give 2% CO_2 benefit and be suitable for buses

Guide to Technology Summaries

Option Label

Brief description of the concept, with relevant examples of prototype vehicles or commercial products.

High level estimates of technology TRL, fuel savings and CO_2 benefit, cost for one vehicle, changes to running costs are provided for INDICATION ONLY.



"Step 1" lightweighting is achieved through relatively modest design changes

"Step 1" lightweighting

- **Description:** "Step 1" lightweighting is assumed to be approx. 7.5% kerb mass reduction, achieved through relatively modest design changes which could typically be done by the bus OEM / coachbuilder for the chassis and body structure:
  - Optimisation of existing bus structure (down gauging)
  - Application of high strength steels on chassis frame
  - Application of higher grade aluminium to body structure
  - No change to powertrain and axle systems
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: all materials are available and currently used in bus industry, TRL varies depending on system
- **Potential Fuel Savings and CO_2 Benefit:** approx. 3% CO_2 benefit for both single and double deck buses
- **Technology Price:** increase in technology price due to a shift to lighter but more expensive materials
- **Maintenance Cost:** no increase to annual costs expected
- **Retro-fit potential:** No

	SD	DD
TRL	6/7	6/7
Development to TRL 9	Medium	Medi
TTW CO_2 Benefit (%)	3	3
Technology Price (£)	6,000	10,000
Maintenance Cost (£)	-	-

Volvo bus chassis made with lightweight bolted steel frame

Picture Source: Volvo B7R

Source: www.volvobuses.com

© Ricardo plc 2012 31

Technology data for single and double deck vehicles

Technology readiness level (TRL as described on the next slide)

Development effort (broadly defined as man years effort) required to bring the technology to market (TRL9) (low/medium/high)

% CO_2 reduction in Tank to Wheels (TTW) and/or Well to Wheels (WTW) terms

Estimated technology price

Estimated change in annual running cost

List of sources used to gather data for option evaluation

Picture to illustrate an example of the option

Technology Readiness Levels (TRL) have been used to describe the state of a technology's development

TRL 1	• Basic principles observed and reported • Paper studies and scientific studies have been undertaken
TRL 2	• Speculative applications have been identified • Application specific simulations or experiments have been performed
TRL 3	• Analytical and lab studies have physically validated predictions of individual technology elements or components which are no t yet integrated or representative
TRL 4	• Technology components and/or basic subsystems have been validated in lab or test house environment • Basic concept observed in other industry sectors
TRL 5	• Technology components and/or basic system have been validated in relevant environment – potentially through a mule or modified production vehicle
TRL 6	• Model or prototype of the system has been demonstrated as part of a vehicle which can simulate and validate all system specifications within an operational environment (e.g. Test track)
TRL 7	• Multiple prototypes have been demonstrated in an operational environment. Similar or identical product has been tested in a similar operating cycle to application under consideration
TRL 8	• Test and demonstration phases have been completed to customers' satisfaction. Press releases/marketing of saleable product • Technology has been proven to work in its final form and under all expected conditions
TRL 9	• Real world deployment and performance of the technology is a success. Product is being sold off production tooling in reasonable volumes

Source: Adapted from LowCVP

Contents

Lightweighting introduction

- Lightweighting describes the process of optimising material geometry and specification in order to achieve a mass reduction when compared to an existing design. Most often removing weight from a structure can compromise the performance (stiffness, strength) or incur a cost increase. Lightweight optimisation involves the careful consideration and evaluation of these parameters. Differing degrees of weight optimisation can result in different cost and performance trade-offs.
- This report considers a 2 step approach:
  - "Step 1" lightweighting is achieved through relatively modest design changes (summarised on slide 34):
    - Approx. 7.5% kerb mass reduction
    - 3% CO_2 benefit
    - Cost of £6,000 – £10,000
  - "Step 2" lightweighting is achieved via more extreme design changes (summarised on slide 35):
    - Approx. 15% kerb mass reduction
    - 7 – 7.5% CO_2 benefit
    - Increased cost of £18,000 – £25,000
  - A further step was deemed inappropriate for buses as it would require extensive use of carbon fibre for unrealistic price increases, approx. £50,000 – £100,000 per bus
- A combination of Steps 1 and 2 could be carried out to increase the CO_2 benefit

“Step 1” lightweighting is achieved through relatively modest design changes

“Step 1” lightweighting

- **Description:** “Step 1” lightweighting is assumed to be approx. 7.5% kerb mass reduction, achieved through relatively modest design changes which could typically be done by the bus OEM / coachbuilder for the chassis and body structure:
  - Optimisation of existing bus structure (down gauging)
  - Application of high strength steels on chassis frame
  - Application of higher grade aluminium to body structure
  - No change to powertrain and axle systems
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: all materials are available and currently used in bus industry, TRL varies depending on system
- **Potential Fuel Savings and CO_2 Benefit:** approx. 3% CO_2 benefit for both single and double deck buses
- **Technology Price:** increase in technology price due to a shift to lighter but more expensive materials
- **Maintenance Cost:** no increase to annual costs expected
- **Retro-fit potential:** No

	SD	DD
TRL	6/7	6/7
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	3	3
Technology Price (£)	6,000	10,000
Maintenance Cost (£)	-	-

Volvo bus chassis made with lightweight bolted steel frame

Picture Source: Volvo B7R

Source: www.volvobuses.com

“Step 2” lightweighting is achieved via more extreme design changes

“Step 2” lightweighting

- **Description:** “Step 2” lightweighting is assumed to be approx. 15% kerb mass reduction, achieved via more extreme design changes which require new developments from Tier 1 suppliers:
  - Introduction of new Tier 1 lightweight powertrain, axle (aluminium), wheels, tyres and brakes
  - Aluminium chassis frame
  - Polycarbonate / SMC exterior panels
  - New lightweight seating (similar to aerospace industry trend)
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: TRL varies depending on system
- **Potential Fuel Savings and CO_2 Benefit:** approx. 7% and 7.5% CO_2 benefit for single and double deck buses respectively
- **Technology Price:** further increase in technology price due to a shift to lighter but more expensive materials
- **Maintenance Cost:** no increase to annual costs expected
- **Retro-fit potential:** Some modifications may be retrofitted, eg lightweight seating, axles and driveline

	SD	DD
TRL	5/6	5/6
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	7	7.5
Technology Price (£)	18,000	25,000
Maintenance Cost (£)	-	-

Volvo bus body structure comprising aluminium profiles that are screwed together and aluminium roof

Picture Source: Volvo 7900 Diesel B9L Chassis

Source: http://busevi.com/index.php?view=article&id=639%3Anew-volvo-7900&option=com_content&Itemid=3

Contents

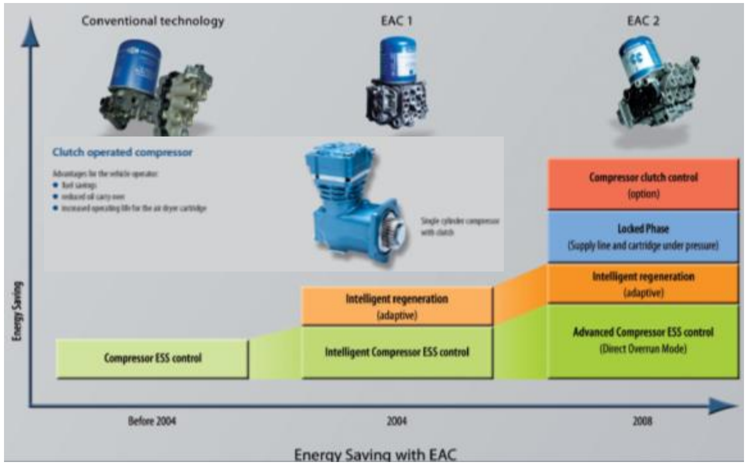
Smart / Clutched Compressor is driven on overrun only

Smart / Clutched Compressor (e.g. Knorr Bremse EAC)

- **Description:** control of compressor parasitic load on engine either via depressurisation and/or declutching , the compressor can be disengaged when not required. With smart control the compressor is only engaged when the vehicle is in deceleration (overrun) phase, significantly reducing idle / on load parasitics
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: TRL8
  - Development for bus application: Systems have been developed for HGV, expected to be transferable
- **Potential Fuel Savings and CO_2 Benefit:** CO_2 benefit of approx. 6% for both single and double deck buses based on proportion of power to ancilliaries and cycle spent in overun
- **Technology Price:** Technology cost estimated from figures given by Knorr Bremse for Pneumatic Booster System, which uses broadly similar components
- **Maintenance Cost:** system includes air filter monitoring component, so may slightly reduce filter cartidge change rate;
- **Retro-fit potential:** Can be retrofitted – compressor is accessible at engine accessory drive, EAC filter/drier module replaces existing unit

Source: K-B publications: Y062165_EN_001[1].pdf & P-3505_EN_005[1].pdf

	SD	DD
TRL	8	8
Development to TRL 9	L	L
TTW CO_2 Benefit (%)	6	6
Technology Price (£)	600	600
Maintenance Cost (£)	-	-



Picture Source: K-B publications

Smart Alternator charges the battery on the overrun only

Smart Alternator (Overrun Only)

- **Description:** Control of alternator excitation so that the alternator **only** charges the battery under deceleration (overrun) conditions
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: technology becoming semi-mainstream for passenger cars; functionality available on Mercedes Benz Citaro bus
- **Potential Fuel Savings and CO_2 Benefit:** CO_2 benefit of approx. 6% for both single and double deck buses based on proportion of power to ancilliaries and cycle spent in overun
- **Technology Price:** Based on scaled costs for passenger car unit
- **Maintenance Cost:** no change to annual costs expected;
- **Retro-fit potential:** Can be retrofitted – alternator is accessible at engine accessory drive, requires interface to engine EMS to detect overrun

	SD	DD
TRL	8	8
Development to TRL 9	L	L
TTW CO_2 Benefit (%)	5	5
Technology Price (£)	500	500
Maintenance Cost (£)	-	-

Picture Source: Mercedes-Benz (Citaro)

Source: . http://4.bp.blogspot.com/-AKczZ1R_0/T7_uC40YxJI/AAAAAAAAEe0/JB7JjxKRZ0c/s320/The+All+New+Mercedes-Benz+Citaro+Euro+BLUETEC+6+-+l+(62).jpg

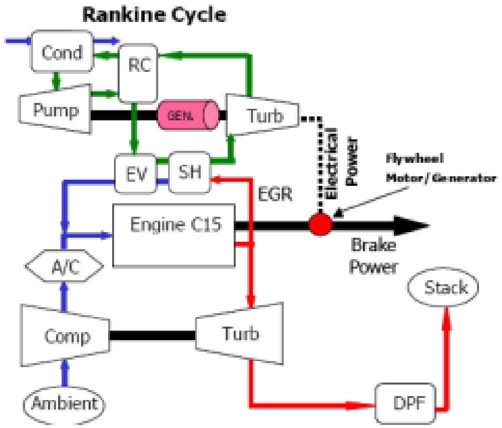
Rankine cycle system generates energy by recovering waste heat from hot exhaust gas or exhaust gas recirculation

Rankine Cycle (Exhaust/EGR)

- **Description:** a Rankine cycle system recovers waste heat from exhaust gas heat via heat exchanger(s) to drive an additional power turbine / expander to generate energy; use energy for ancillaries rather than motive power
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Technology has been validated and is on the market for larger off highway systems. Automotive and HGV systems are in development – in particular validation of the robustness of the expander system is needed
  - Development for bus applications: Validation of system robustness for bus operation
- **Potential Fuel Savings and CO_2 Benefit:** approx. 3% and 4% CO_2 benefit for single and double deck buses respectively – based on Ricardo simulation over MLTB
- **Technology Price:** relatively high technology price
- **Maintenance Cost:** no increase to annual costs expected
- **Retro-fit potential:** Challenging to retro fit – major intervention in engine bay/cooling system.

Source: Caterpillar

	SD	DD
TRL	6	6
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	3	4
Technology Price (£)	9,000	12,000
Maintenance Cost (£)	-	-



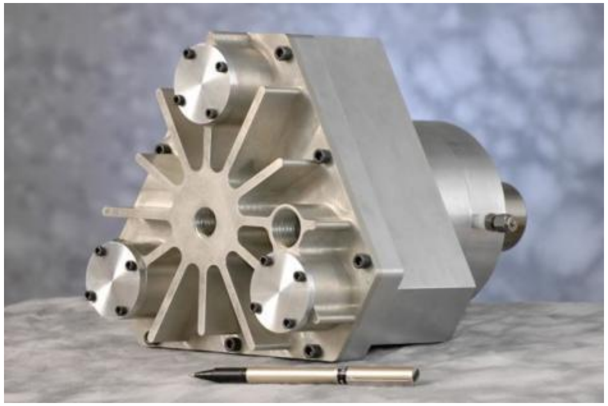
Picture Source: Caterpillar layout for HECC HPL EGR waste heat recovery system – Rankine

Rankine cycle system generates energy by recovering waste heat from coolant heat from heat exchanger

Rankine Cycle (Coolant)

- **Description:** a Rankine cycle system recovers waste heat from coolant via heat exchanger (s) to drive an additional power turbine / expander to generate energy; use energy for ancillaries rather than motive power
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Technology has been validated and is on the market for larger off highway systems. Automotive and HGV systems are in development – in particular validation of the robustness of the expander system is needed
  - Development for bus applications: Validation of system robustness for bus operation
  - **Potential Fuel Savings and CO_2 Benefit:** approx. 3% CO_2 benefit for single and double deck buses – based on Ricardo simulation over MLTB
- **Technology Price:** relatively high technology price
- **Maintenance Cost:** no increase to annual costs expected
- **Retro-fit potential:** Challenging to retro fit – major intervention in engine bay/cooling system.

	SD	DD
TRL	6	6
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	3	3
Technology Price (£)	9,000	12,000
Maintenance Cost (£)	-	-



Picture Source: Air Squared Expander

Source: Ricardo Analysis...

Infinitely Variable Transmission (IVT) is a variant of a continuously variable transmission (CVT)

Infinitely Variable Transmission (IVT)

- **Description**: An infinitely variable transmission is a continuously variable transmission (without discrete gear "steps") that includes a zero ratio to give an effective neutral gear. Toroidal IVTs have been tested on buses to date.
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 6
  - Development for bus application: System is currently under development by Allison for bus application, development is required for durability in real world conditions
- **Potential Fuel Savings and CO_2 Benefit:** IVT's reduce fuel consumption by allowing the engine to operate at it's most efficient point. Expected to give CO_2 benefit of approx. 15% compared to a standard manual transmission - based on Torotrak application to an Optare bus tested on a chassis dynamometer over MLTB cycle
- **Technology Price:** based on Torotrak estimates
- **Maintenance Cost:** no change expected
- **Retro-fit potential:** Can be retrofitted, transmission change straightforward as long as alternative mountings can be accomodated

	SD	DD
TRL	6	6
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	15	15
Technology Price (£)	15,000	15,000
Maintenance Cost (£)	-	-

Picture Source: Torotrak

Source: SAE 2007-01-4206 ' Fuel Economy Benefits of a high torque Infinitely Variable Transmission for Commercial vehicles, D J Burtt, Torotrak ...

Contents

Introduction – Hybrid Powertrain Systems

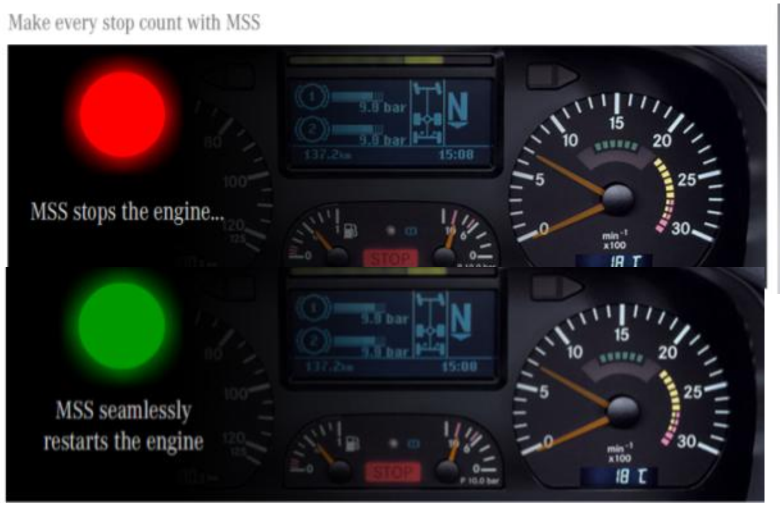
- A hybrid system enables energy to be recovered during braking and then released to accelerate the vehicle or to power the vehicle’s hotel load while its main engine is turned off
  - A typical stop/start architecture simply has the capability to start and stop the engine very quickly to reduce idling time
  - A mild hybrid architecture typically has the following capabilities: engine stop/start; regenerative braking; torque assist; and limited electric only traction mode. Depending on the type/size of storage it could maintain power to the vehicle when the engine is off
  - A full hybrid architecture has the same features as a mild hybrid, but typically with higher power capability and more energy storage, with the possibility of a fully electric traction mode
- These systems can be used with many different types of energy storage or power source, for example with batteries or flywheels
- Hybrid cars and buses have been in production for a number of years and hybrids are in development for low volume production for other sectors including heavy duty trucks and marine
  - As a consequence, a wide range of components and systems are becoming available
- The fuel consumption benefit from hybridisation is directly dependent on duty cycle
  - As a result, buses operating in an urban environment with frequent speed changes will see a much more significant saving than an intercity or coach service

Stop / start battery systems have potential to offer good CO_2 benefits over the bus duty cycle at relatively low cost

Stop / Start Battery System

- **Description:** Stop-start system reduces fuel used during idle by stopping the engine when the vehicle is stationary, and ancillary loads can be sustained . Uses a ruggedised starter motor for low cost and reliability, with modified EMS strategies to support
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: currently widely used on light vehicles and offered on some MD, HD truck and bus applications. >62% of Japanese city buses have stop-start and idle shutdown is manadatory in some legislations
  - Development for bus application; already offered by M-B on Citaro. Tier 1 has developed suitable starter motor, durability testing, EMS strategy modifcations and AGM PbA battery
- **Potential Fuel Savings and CO_2 Benefit:** very dependent on duty cycle. MLTB cycle shows ~30% idle state - it is assumed that 50% of bus stops are congestion stops, where stop start is implemented (ie. where less power for doors, etc. is required), CO_2 benefit expected to be approximately 9%
- **Technology Price:** based on extrapolated pass car solutions
- **Maintenance Cost:** allow £500pa for starter maintenance
- **Retro-fit potential:** Possible as long as EMS can support

	SD	DD
TRL	7	7
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	9	9
Technology Price (£)	1,400	1,400
Maintenance Cost (£)	500	500



Picture Source: Mercedes Axor MSS

Source: http://www2.mercedes-benz.co.uk/content/unitedkingdom/mpc/mpc_unitedkingdom_website/en/home_mpc/truck/home/new_trucks/motor_stop_start0.html

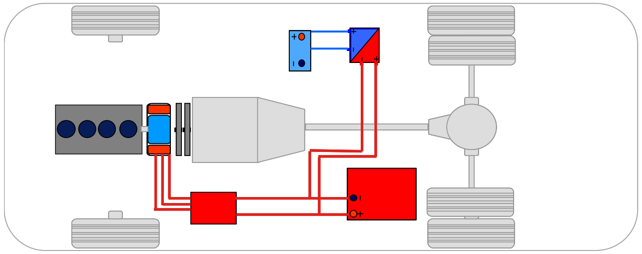
Mild Hybrid System contains stop / start system but also recovers braking energy

Mild Hybrid System

- **Description:** System uses 48V e-motor mounted to the crankshaft to operate stop / start and recover braking energy; recovered energy is used to boost acceleration and could also cover hotel loads; combines well with electrified ancillaries
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: currently used in other sectors
  - Development for bus application: Requires suitable motor for crank mounting, inverter, engine durability testing for new operational modes, EMS strategy modifcations, DCDC for 24V legacy loads, revised battery (Li-ion or Adv PbA).
- **Potential Fuel Savings and CO_2 Benefit:** CO_2 savings expected to be around 13%, benefit, increase over stop start due to regen braking, torque assist and some electrification of ancillaries. Estimate for CO_2 benefit derived from Ricardo mild hybrid system simulation.
- **Technology Price:** Based on extrapolation of passenger car system (at low volume for motor)
- **Maintenance Cost:** no change to annual costs expected
- **Retrofit potential:** Possible but challenging vehicle package

	SD	DD
TRL	4	4
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	13	13
Technology Price (£)	6,000	6,400
Maintenance Cost (£)	-	-

Mild Hybrid Example Layout



Picture Source: Ricardo

Source: Ricardo Analysis...

Hybrid diesel systems save fuel by capturing braking energy therefore duty cycles with more decelerations recover more energy

Full Hybrid System – Parallel

- **Description:** Electric/diesel hybrid where electrical power is routed to/from the wheels in parallel to the mechanical drive from the engine. Direct drive via a relatively conventional transmission remains between the engine and wheels
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Several production ready solutions available for bus application
- **Potential Fuel Savings and CO_2 Benefit:** A range of CO_2 benefits are claimed for parallel hybrid buses - Volvo B5L TfL 30% (July 2009), Volvo 7700/7900 SD 30-37% (various publication dates);
- **Technology Price:** Double deck cost higher due to increased weight which requires slightly larger parts for motor / inverter
- **Maintenance Cost:** small reduction in brake maintenance due to wear reduction facilitated by regenerative braking is significantly outweighed by battery replacement cost. Estimate 5 years life, (hugely affected by duty cycle, ambient conditions). Expected pack replacement price $350/kWh = £25k-£30k
- **Retrofit Potential:** Challenging vehicle package and safety implications due to high voltage system

Source: Ricardo Analysis...

	SD	DD
TRL	9	9
TTW CO_2 Benefit (%)	35	35
Technology Price (£)	90,000	105,000
Maintenance Cost (£)	3270	3940

Picture Source: Volvo 7700 Hybrid

Hybrid diesel systems save fuel by capturing braking energy therefore duty cycles with more decelerations recover more energy

Full Hybrid System – Series

- **Description:** Electric/diesel hybrid without conventional transmission, engine generates electricity that is stored in a battery and used to power a separate traction motor. Electrical machines/battery are higher power than in equivalent parallel
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Wrightbus DD deck series full hybrid demonstrator vehicle already in service with TfL
- **Potential Fuel Savings and CO_2 Benefit:** Wrightbus DD achieves 40%, more regen opportunities than parallel
- **Technology Price**: Series cost slightly lower than parallel due to smaller battery size and more straightforward integration. Wrightbus total double deck bus cost £300,000 – £315,000
- **Maintenance Cost:** small reduction in brake maintenance due to wear reduction facilitated by regenerative braking is significantly outweighed by battery replacement cost. Estimate 5 years life, (hugely affected by duty cycle, ambient conditions). Expected pack replacement price $350/kWh = £25k-£30k
- **Retrofit Potential:** Challenging, marginally easier than parallel, but still has significant package and safety constraints

	SD	DD
TRL	9	9
TTW CO_2 Benefit (%)	40	40
Technology Price (£)	75,000	90,000
Maintenance Cost (£)	3940	4610

Picture Source: Wrightbus

Source: Wrightbus; NBfL article at www.guardian.co.uk on 22/12/11

High Speed Flywheels store energy in a kinetic form

High Speed Flywheels

- **Description:** An additional high speed flywheel that stores and releases energy from/to the vehicle driveline. The flywheel stores energy, while braking for example, releasing it to supplement or temporarily replace the engine output. Flywheel technology described here does not include stop start functionality
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: TRL5/6 – Flywheel hybrid systems for buses are under development by a number of manufacturers
- **Potential Fuel Savings and CO_2 Benefit:** expected to give CO_2 benefit of approx. 17%, based on Ricardo system analysis
- **Technology Price**: Currently estimated at ~£15k, based on published payback times for application to bus
- **Maintenance Cost:** reduction in brake maintenance costs due to wear reduction facilitated by regenerative braking
- **Retro-fit potential:** Suitable for retro-fit – costs expected to be similar for retrofit and OEM system

	SD	DD
TRL	5/6	5/6
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	17	17
Technology Price (£)	15,000	15,000
Maintenance Cost (£)	-60	-60

Picture Source: Ricardo

Source: .Williams hybrid power, Ricardo

Hydraulic Hybrid Systems store energy using a compressed fluid

Hydraulic Hybrid System – Parallel

- **Description:** Parallel hydraulic hybrid stores braking energy in a hydraulic accumulator and then reuses that energy to assist the vehicle drive. Hydraulic energy transfer via swashplate/axial piston type hydraulic pump/motor, retains (relatively) conventional transmission.
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Bosch Rexroth single deck parallel hydraulic hybrid demonstrator vehicle already exists
- **Potential Fuel Savings and CO_2 Benefit:** Bosch Rexroth estimate 25% CO_2 benefit for commercial vehicles however this is likely to be slightly less when applied to buses, estimated at 20%
- **Technology Price:** cost estimate based on public domain information
- **Maintenance Cost:** Small increase associated with hydraulic system servicing, filters, accumulator charging etc, reduction in brake wear
- **Retro-fit potential:** Challenging vehicle package but eliminates safety requirements associated with HV systems, has been retrofitted in the past

Source Bosch Rexroth: ...

	SD	DD
TRL	7	7
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	20	20
Technology Price (£)	37 500	37 500
Maintenance Cost (£)	-60	-60

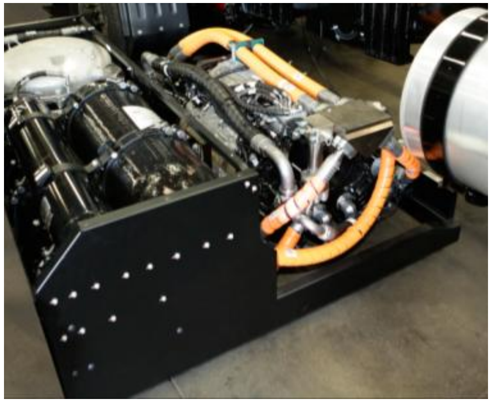
Picture Source: Bosch Rexroth Hydraulic Hybrid Brochure

Both parallel and series configurations are possible for hydraulic hybrids

Hydraulic Hybrid System – Series

- **Description:** Hydrostatic drive, engine drives hydraulic pump, wheels are driven by hydraulic motor, no direct connection between engine and wheels. Stores braking energy in a hydraulic accumulator and then reuses that energy to assist the vehicle drive.
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Parker RunWise series hydraulic hybrid demonstrator vehicle already exists. Altair have developed a hydraulic series hybrid demontrator bus
- **Potential Fuel Savings and CO_2 Benefit:** Parker estimate 30 – 50% CO_2 benefit for commercial vehicles however this is likely to be slightly less when applied to buses, approx. 35%, as they stop less frequently than refuse trucks
- **Technology Price:** cost estimate based on public domain information
- **Maintenance Cost:** Small increase associated with hydraulic system servicing, filters, accumulator charging etc
- **Retro-fit potential:** Challenging vehicle package but eliminates safety requirements associated with HV systems, has been retrofitted in the past

	SD	DD
TRL	7	7
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	35	35
Technology Price (£)	37 500	37 500
Maintenance Cost (£)	-60	-60



Picture Source: Parker RunWise Hydraulic Hybrid Brochure

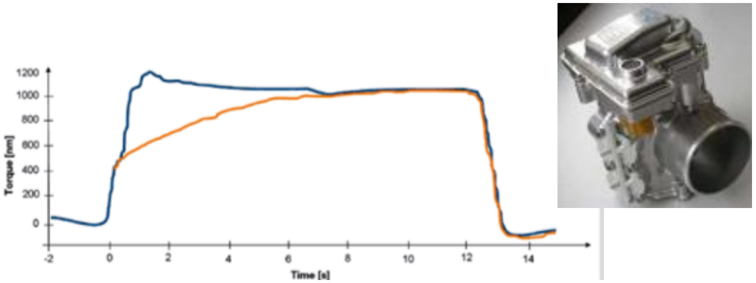
Source: http://greenbigtruck.com/2011/09/altair-unveils-series-hydraulic-hybrid-transit-bus/, ...

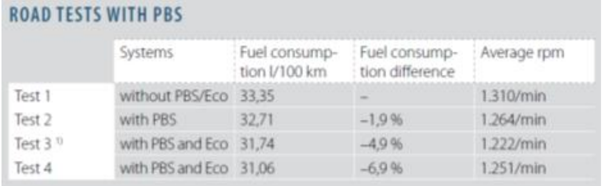
Air hybrid systems such as PBS have potential to reduce CO_2 emissions by using the brake air reservoir to store energy

Pneumatic Booster System (PBS)

- **Description:** Compressed air from vehicle braking system injected into the engine air manifold to improve vehicle acceleration. This allows an earlier gear shift (short shifting).so engine operates more in efficient engine speed / load range
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: expected in the market for trucks late 2012, unit would be similar to that for buses
- **Potential Fuel Savings and CO_2 Benefit:** approx. 3% CO_2 benefit for both single and double deck buses based on Knorr Bremse for HGV, modified based on MTLB cycle analysis
- **Technology Price:** Based on public domain information
- **Maintenance Cost:** no change to annual costs expected
- **Retro-fit potential:** Suitable for retrofit, requires additional component on intake manifold and additional air tank capacity (~80 litres)

	SD	DD
TRL	8	8
Development to TRL 9	L	L
TTW CO_2 Benefit (%)	3	3
Technology Price (£)	600	600
Maintenance Cost (£)	-	-




ROAD TESTS WITH PBS

	Systems	Fuel consumption l/100 km	Fuel consumption difference	Average rpm
Test 1	without PBS/Eco	33,35	–	1.310/min
Test 2	with PBS	32,71	–1,9 %	1.264/min
Test 3 [1]	with PBS and Eco	31,74	–4,9 %	1.222/min
Test 4	with PBS and Eco	31,06	–6,9 %	1.251/min

Picture Source: Knorr-Bremse PBS System

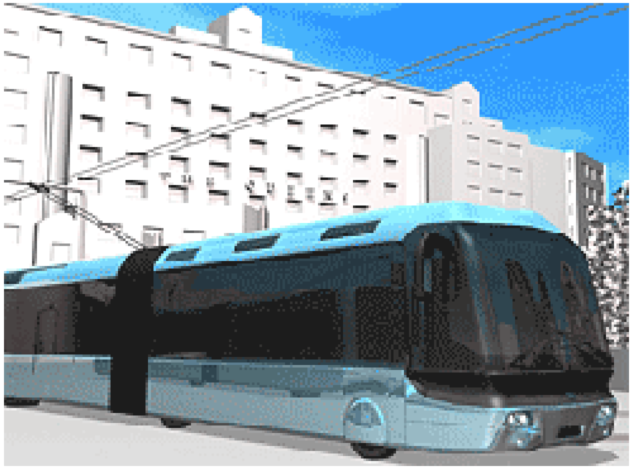
Source: Knorr Bremse PBS Y135981_EN_000[1].pdf, lastauto omnibus road test

Trolleybuses are powered by overhead electrical cables

Trolleybus (Overhead Line or Ground Contact)

- **Description:** electric powered rubber tyred bus with current collection either via overhead line (catenary) or ground contact (sensors ensure only contact rail is energised for safety on the Bombardier Primove system)
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: TRL 9, mature technlogy
- **Potential Fuel Savings and CO_2 Benefit:** Trolleybuses give 100% TTW CO_2 benefit. WTW CO_2 benefit depends on electricity production methods. On current UK grid mix (164 g CO_{2eq}/MJ) WTW CO_2 is reduced by 24% compared to a diesel bus. Obviously this could be improved by decarbonizing the UK grid
- **Technology Price:** infrastructure cost is high; costs shown in the table are vehicle only; if typical infrastructure costs for 50 veh / 50km system are added this rises by £8.5m per vehicle. Leeds system recently announced would be central Government funded by £170m out of £250m total (subsidy level of 68%). Further information on costs shown on slide 53
- **Maintenance Cost:** Not known, unlikely to be significantly different to bus

	SD	DD
TRL	9	9
TTW CO_2 Benefit (%)	100	100
WTW CO_2 benefit (%)	24	24
Technology Price (£)	300 000	500 000
Maintenance Cost (£)	-	-



Picture Source: Leeds NT

Source: Leeds NT http://www.ngtmetro.com/ CONCAWE 2011

Trolleybus costs are estimated based on relatively scarce public domain information

- Cost information on trolleybuses is difficult to find in a comparable form to the other low carbon bus technologies, due to the inclusion of infrastructure costs
- Estimates used in this study for vehicle price were single deck £300k, Double deck (actually bendy/artic) £500k
  - A summary of public domain information used to develop these estimates is shown below:

- Leeds NGT give an overall system (infrastructure + vehicles) cost of £250m for a 9 mile route (in total £28m/double track mile (dtmi))
- Leeds NGT cost breakdowns detail the split between infrastructure cost and vehicle cost:
  - Of the £250m quoted above, £190m is the base project cost
  - This is further subdivided into £127m construction cost (working out at ~£14m/dtmi, compare £4m for mainline rail electrification), and £11.4m for 19 vehicles - £600k per vehicle
- The Electric Trolleybus UK (www.tbus.org.uk) group give figures of £20m/dtkm (£32m/dtmi) which show reasonable agreement with the Leeds figures

- Tbus UK claims that trolleybuses currently cost double (100% increase) a conventional diesel bus due to low volumes, but this could reduce to 20% more than a diesel bus with economies of scale and technology commonality with conventional buses
- Based on this study's baseline bus costs, this would translate to a range of £160-£420k for single/double trolleybuses
- Between these two separate sources (with their different view points) we see a range of £160-£600k for vehicle costs

Source: Leeds NGT http://www.ngtmetro.com/ ; www.tbus.org.uk; collections.europarchive.org/tna/...dft...uk/.../rail/.../rail-electrification...

CO_2 savings from Battery Electric Vehicles depend on grid mix

Battery Electric Vehicles

- **Description:** Vehicle is driven by an electric motor powered by batteries which are charged from mains electricity. The vehicle has no other power source other than the battery
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: EV buses deployed around the world in commercial service for ~2years
- **Potential Fuel Savings and CO_2 Benefit:** Electric vehicles have give 100% TTW CO_2 benefit. WTW CO_2 benefit depends on electricity production methods. On current grid mix (164 g CO_{2eq}/MJ) WTW CO_2 is reduced by 30% compared to a diesel bus over the MLTB.
- **Technology Price:** Technology costs for double deck is higher than single due to additional batteries needed due to higher vehicle mass. Price does not include charging infrastructure costs
- **Maintenance Cost:** Battery replacement cost significant. BYD estimate 4500 cycles/12-15years life. More conservative estimate might be 10years, in-service life will be hugely affected by duty cycle, ambient conditions and charge rate. Typical pack replacement cost $350/kWh for volume manufacture

	SD	DD
TRL	9	9
TTW CO_2 Benefit (%)	100	100
WTW CO_2 benefit (%)	30	30
Technology Price (£)	97 500	105 000
Maintenance Cost (£)	4940	6610

Picture Source: Optare

Source: Optare http://www.optare.com/images/hi_res/durhamev2.JPG, CONCAWE 2011

Fuel Cell systems have the potential to power vehicles, such as buses and medium duty trucks, with zero tailpipe emissions

Fuel Cell

- **Description:** fuel cells convert the chemical energy of hydrogen into electrical energy that can be used to power the vehicle. For bus applications, a hybrid Polymer Electrolyte Membrane (PEM) fuel cell system could be used as the prime mover for the vehicle
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: single deck fuel cell bus trials in numerous cities across the globe; no double deck fuel cell bus demonstrators currently available
  - Packaging fuel cell systems is challenging for a double deck bus – added height and structural considerations mean that the roof is not suitable and under floor package space is limited by low floor capability
- **Potential Fuel Savings and CO_2 Benefit:** Hydrogen fuel cells 100% CO_2 TTW benefit. WTW CO_2 benefit 17%-94% depending on H_2 pathway (range from industrial steam reforming to nuclear electrolysis). This is discussed in the Alternative Fuels section
- **Technology Price:** A fuel cell bus today costs 3 – 6 times more than the price for a conventional bus, price doesn't include hydrogen refuelling infrastructure
- **Maintenance Cost:** significantly higher than the baseline diesel bus and require special workshops/procedures

Source: CONCAWE 2011...

	SD	DD
TRL	7	3
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	100	100
WTW CO_2 Benefit (%)	17-94	17-94
Technology Price (£)	600,000	700,000
Maintenance Cost (£)	10000	10000

Picture Source: Icelandic New Energy

Contents

This section reviews fuels that are expected to be suitable for bus use, with consideration of WTW CO_2 emissions

- This section includes discussion and technology summaries for fuels which are expected to offer an alternative to diesel in internal combustion engines for bus use
- For alternative fuels (especially biofuels) the well-to-tank (WTT) pathway is where significant CO_2 benefits lie
  - The focus of this section is therefore on WTT CO_2 emissions
- Some fuels also affect TTW CO_2, for example CNG and Biomethane
  - For these fuels both TTW and WTT CO_2 emissions are detailed
- Discussion included in this section includes the following topics, followed by technology summaries

Biofuels

  - Identification of public domain WTT/WTW CO_2 figures for different biofuels
  - Brief commentary on the impacts biofuels could have on the efficiency of the low carbon technologies considered in the study

CNG

  - The effect of CNG use on TTW and WTW CO_2 emissions
    - The effect of fugitive methane emissions is considered
  - Consideration of the relative WTW efficiency of the use of CNG direct from the UK gas network, and whether this pathway has lower CO_2 emissions than other CNG pathways

This table shows the alternative fuels for Internal Combustion Engines (ICE) that have been considered in this study

Source	**Liquid fuels**		**Gaseous fuels**		
	Diesel-like fuel	Other liquid fuels	Methane	Propane	Hydrogen^
Fossil	EN590 road diesel*	DME***	CNG	LPG	Industrial (steam reformed) H2
	Coal to liquid **(CTL)		LNG		
	Gas to liquid **(GTL)				
Bio	HVO	Bioethanol	Biomethane		Renewable H2
	2G bio (BTL)	Bio DME			
	1G bio (FAME)*	Biomethanol			

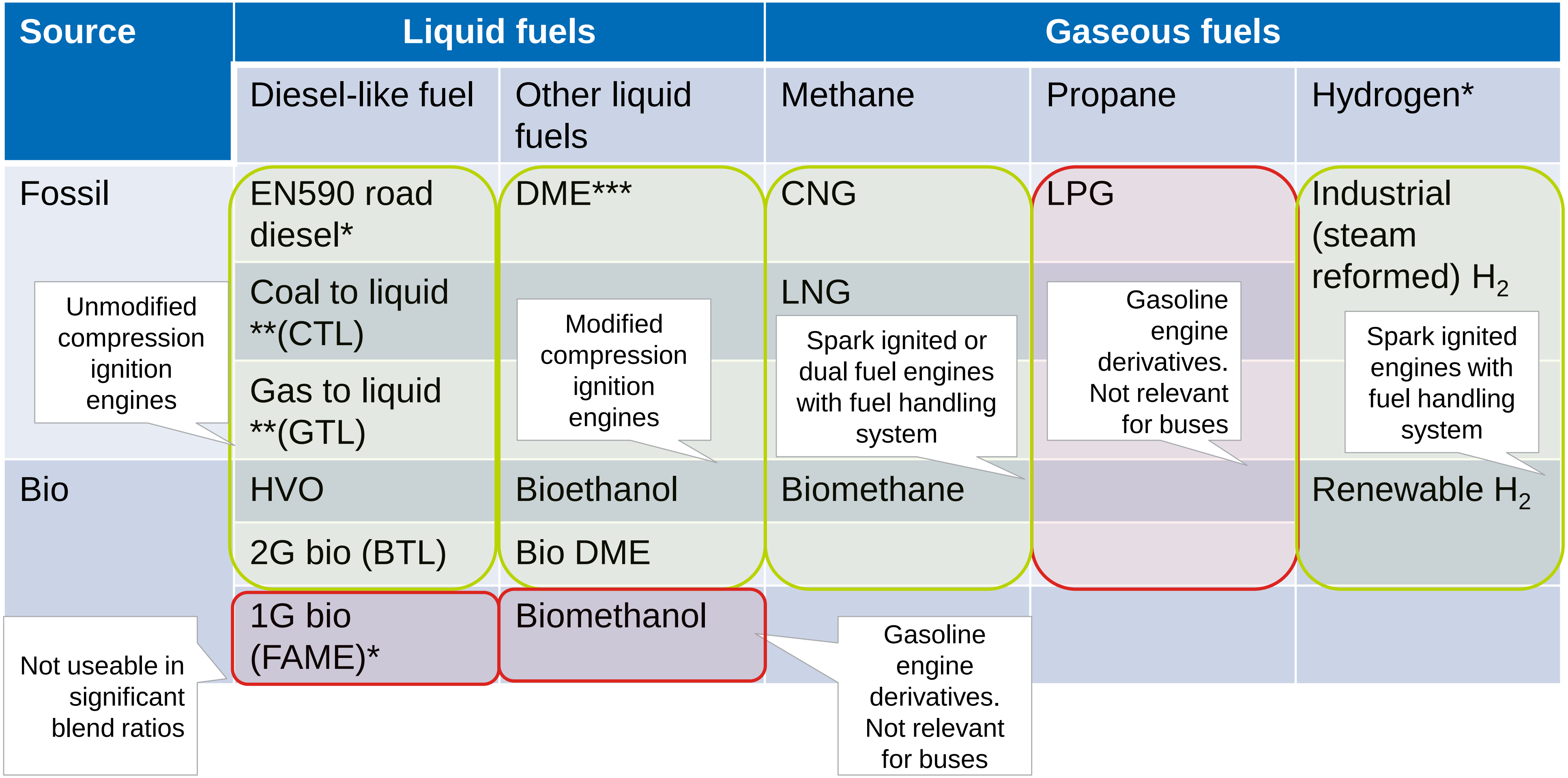
*EN590 spec allows 93% fossil and 7% 1G biodiesel (FAME) and so straddles the fossil/bio division. For the purposes of this study it is considered the baseline fuel

** although GTL/CTL processes produce high quality diesel fuel they are not common European processes and have limited CO_2 benefit

*** although fossil based DME is possible, it is bio DME which is of significant interest

^ Hydrogen can be consumed in both ICE and fuel cell, fuel cell (alternative powertrain) covered on slide 55

Not all fuels are suitable for bus application in the UK – fuels that are considered to be unsuitable are shaded red in the table below



Source	Liquid fuels		Gaseous fuels		
	Diesel-like fuel	Other liquid fuels	Methane	Propane	Hydrogen*
Fossil	EN590 road diesel*	DME***	CNG	LPG	Industrial (steam reformed) H_2
	Coal to liquid **(CTL)		LNG		
	Gas to liquid **(GTL)				
Bio	HVO	Bioethanol	Biomethane		Renewable H_2
	2G bio (BTL)	Bio DME			
	1G bio (FAME)*	Biomethanol			

Unmodified compression ignition engines

Modified compression ignition engines

Spark ignited or dual fuel engines with fuel handling system

Gasoline engine derivatives. Not relevant for buses

Spark ignited engines with fuel handling system

Not useable in significant blend ratios

Gasoline engine derivatives. Not relevant for buses

*Note: Hydrogen can also be consumed in a fuel cell to generate electricity or burnt in an ICE. The same WTT characteristics will apply whether the H_2 is consumed in an ICE or FC

Contents

This section considers the use of biofuels for bus application

Source	Liquid fuels		Gaseous fuels		
	Diesel-like fuel	Other liquid fuels	Methane	Propane	Hydrogen*
Fossil	EN590 road diesel*	DME***	CNG	LPG	Industrial (steam reformed) H_2
	Coal to liquid **(CTL)		LNG		
	Gas to liquid **(GTL)				
Bio	HVO	Bioethanol	Biomethane		Renewable H_2
	2G bio (BTL)	Bio DME			
	1G bio (FAME)*	Biomethanol			

Biofuels under consideration in this study include first and second generation biodiesel in addition to HVO, E95, DME and biomethane

- Biodiesel
  - First generation (only up to 7% blend)
  - Second generation (BTL) substitutional up to 100%
- Hydrotreated vegetable oil (HVO)
- Bioethanol (E95)
- Dimethyl Ether (DME)
- Biomethane (CBG)
- Renewable H_2*

Source	**Liquid fuels**		**Gaseous fuels**		
	Diesel-like fuel	Other liquid fuels	Methane	Propane	Hydrogen*
Fossil	EN590 road diesel*	DME***	CNG	LPG	Industrial (steam reformed) H_2
	Coal to liquid **(CTL)		LNG		
	Gas to liquid **(GTL)				
Bio	HVO	Bioethanol	Biomethane		Renewable H_2
	2G bio (BTL)	Bio DME			
	1G bio (FAME)*	Biomethanol			

*When used in a fuel cell H_2 can be considered an energy vector (transferring electrical energy). When burned in an ICE it may be considered a renewable fuel if sourced via renewably powered electrolysis

Biodiesel and HVO are suitable for use in buses – but the proportion of 1G biodiesel is limited by engine durability concerns and supplies of 2G bio/HVO are limited

- **Biodiesel:**
  - 1st generation (1G) biodiesel (FAME) is only permitted by fuel specification up to 7% blend ratio with diesel (B7) and is only warranted by OEMs at this level
    - Higher blends are not supported by OEMs due to concerns over fuel quality and stability
    - Current pump fuel spec allows up to 7%, typical actual content is assumed to be 5%, and so 1G biodiesel is effectively a baseline technology and will not be considered further
  - 2G biodiesel is of high quality can be considered directly substitutional up to 100%
  - 2G biodiesel (eg, BTL) is expected to be supply side limited for the foreseeable future and is therefore expected to be a niche product in either low or high blend ratios until demand increases and production cost reduce . Likely expected timeframe for widespread introduction is 2025-2030
    - Current global BTL production equates to less than 1% of the European diesel demand
- **HVO**
  - Hydrotreating vegetable oil is a process for upgrading a vegetable oil to a BTL-like liquid fuel.
  - There are no significant concerns about fuel quality or stability, so the fuel could in principle be substitutional up to 100%
  - However like BTL, HVO is supply side limited
  - For reference, current HVO global production equates to only 1% of European diesel demand
  - HVO can use an “oil plant” feedstock (unlike BTL which uses waste) so “food vs fuel” debates may not resolved by choosing HVO
    - HVO can be produced from waste cooking oil

Bioethanol and Bio-DME are renewable liquid fuels requiring engine modification

- **Bioethanol (E95):**
  - Scania have successfully run a fleet of buses on bioethanol in compression ignition engines, using a 95% blend (the balance being 5% combustion enhancer polyethylene glycol). Reliability and maintenance demands are as for diesel buses
  - Engine technology is based on a standard diesel CI engine but with larger injector nozzles (to adjust for the low calorific value) and very high compression ratio. Special surface finishes are required on wet components to resist the corrosive nature of ethanol
  - Bioethanol is primarily sourced from sugar cane, grain/corn/straw or forestry waste
- **Bio-DME**
  - DME is a gas at room temperature but can be liquefied under moderate pressure and injected into a CI engine via a modified diesel fuel injection system. In simple terms, it can be thought of as analogous to an LPG converted gasoline engine
  - DME engines have been promoted in Japan where their inherent soot-free characteristics make them attractive for urban use
  - A fuel handling system (temperature and pressure control) is needed to maintain fuel in a liquid state. Lubricity additives may be needed
  - Bio DME can be sourced with a favourable CO_2 level from forestry waste

Biomethane (CBG) is produced from anaerobic digestion of waste and can be consumed in an unmodified gas engine

- **Biomethane**
  - Digester gas is cleaned and upgraded (removing H_2S, Siloxanes, water and CO_2 and adding propane to increase calorific value where necessary) to produce an equivalent purity to conventional natural gas. Once upgraded the CBG can then be injected into the conventional gas grid
    - The proximity of injection point to end user determines how much upgrading is required
      - Local injection into low pressure network – greater upgrade requirement
      - Injection into medium or high pressure network requires less gas upgrade due to improved mixing/dilution
  - Alternatively biomethane can be liquefied and tankered to the consumer
  - Biomethane can also be generated from sewage plants and landfill sites
    - Many of these facilities already have local power generation schemes consuming the CBG
  - The prime biomethane pathway for the UK is expected to be through dedicated Anaerobic Digestion (AD) plants, using animal/agricultural waste as feedstock. By-products of the AD process include a high grade fertilizer
  - The location of the AD plants relative to feedstock sources/waste consumers, and the gas grid (low/medium/high pressure) will have an impact on the WTT CO_2
  - CBG as a road fuel can be consumed using the same technology as gas fuelled engines (see CNG/LNG section for WTT characteristics)

Source: discussions with GBA and LCVP.

Hydrogen can be formed either from steam reforming in an industrial process or via conventionally or renewably powered electrolysis and can be consumed in an modified gas (SI) engine

- **Hydrogen**
  - Hydrogen has a high mass calorific value and low ignition energy, but low density and hence volumetric calorific value.
  - It can be burned safely in a modified (lowered compression ratio, modified ignition system) SI engine
  - Hydrogen can also be consumed in a fuel cell powertrain to generate electricity for traction motors (covered further in Alternative Powertrain section)
  - Hydrogen when sourced from a conventional industrial steam reforming process has a high carbon intensity.
  - However ,hydrogen can also be formed from the electrolysis of water
    - This process has a low overall energy efficiency, therefore if powered via conventional electricity this also has high carbon intensity
      - However, if powered by renewable electricity the carbon intensity can be very favourable (discussed further in WTT section), although total energy use remains high

Source: discussions with GBA and LCVP.

Well to Tank (WTT) and Tank to Wheels (TTW) figures are combined for biofuel pathways to give expected overall WTW CO_2 reduction

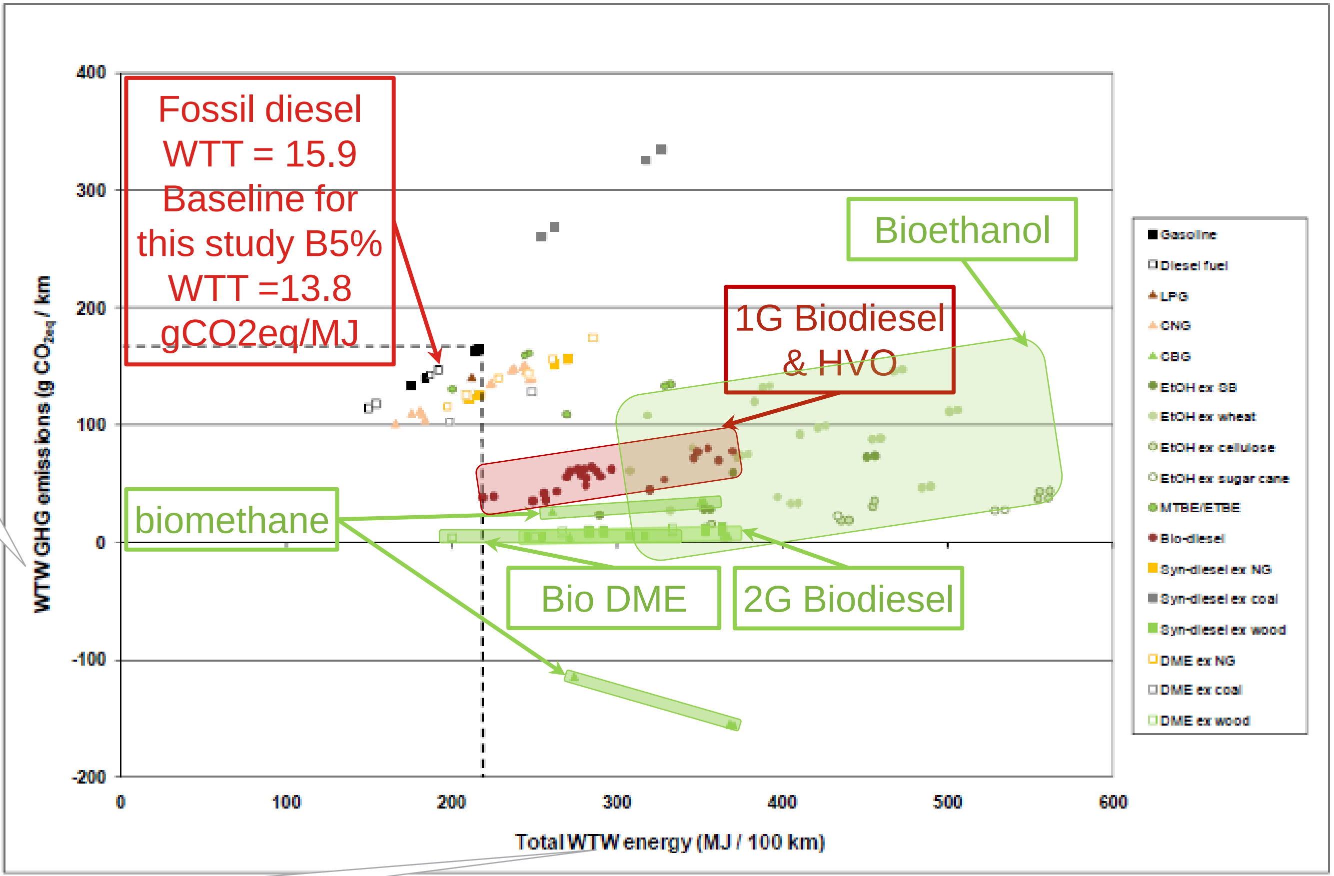
- **WTT** CO_2 emissions figures have been extensively utilized from the CONCAWE report "Well to Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context – Well to Wheels Report Version 3c, July 2011, WTT Appendix 2 – Description and detailed energy and GHG balance of individual pathways", published by the European Commission Joint Research Centre
- **TTW** assessment if is based on Ricardo analysis of bus/heavy duty engine performance
  - TTW aspects covered within the above CONCAWE report are focussed on light duty (car) performance
- In the CONCAWE report GHG includes CO_2, N_2O and CH_4, all reduced to CO_2 eq using established IPCC factors
- **WTW** GHG emissions are then calculated using the expressions below:
  - WTW GHG (gCO_2eq) = TTW GHG (gCO_2eq) + [TTW energy (MJf) x WTT GHG (gCO2eq/MJf)], which leads to the expressions below:
  - WTW GHG (gCO_2eq) = TTW GHG (gCO_2eq) + WTT GHG (gCO_2eq)

Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c)

Biofuels are summarized in the CONCAWE report according to overall WTW GHG emissions and WTW energy requirements

- Note: both GHG & energy axes include a TTW energy term which is for passenger car on NEDC. Whilst lower than the equivalent energy for a bus, this affects all fuel pathways approximately equally, so this figure remains a useful comparison for biofuels

WTW GHG in CO2 eq (accounting for N2O & CH4 according to IPCC factors) = TTW GHG + (TTW energy x WTT GHG per unit of fuel energy)



Fossil diesel WTT = 15.9 Baseline for this study B5% WTT =13.8 gCO2eq/MJ

Bioethanol

1G Biodiesel & HVO

biomethane

Bio DME

2G Biodiesel

WTW energy in fuel production+usage = TTW energy x (1+WTT energy per unit of fuel energy)

WTW

Path-way	Range of WTW CO2 saving
1G bio/ HVO	50-80%
2G bio/ bio DME	90-100%
Bio-ethanol	0-90%
biomethane	90-83% or 176-207%*

*Note WTW saving >100% implies “carbon negative” pathway

Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c)

Because of the wide range of WTT GHG savings from different pathways, it is important to choose the most likely ones. Detailed analysis is in the CONCAWE Appendix (pathway codes given here)

WTT

- **Biodiesel:**
  - 1G biodiesel considered as part of the baseline fuel in this study (assumed B5 for this study)
  - 2G biodiesel (BTL) at B100% using wood, wood waste or pulp by-products as feedstock is the primary route and has been piloted in a number of European plants (not without some commercial difficulties)
    - WWSD1 Woodwaste WTT GHG = -66gCO2eq/MJf
    - WFSD1 Farm wood WTT GHG = -64gCO2eq/MJf
    - BLSD1 Black liquor WTT GHG = - -68gCO2eq/MJf
  - Since all three are rather close in WTT performance and it is difficult to identify the most prevalent pathway in Europe (all are equally feasible) it is logical to use an average WTT value of -66gCO2eq/MJf
  - When converted to a WTW figure in the CONCAWE report this corresponds to a **WTT CO_2 saving over baseline diesel (B5%) of 578%**
- **HVO**
  - Hydrotreating vegetable oil takes the same “oil” feedstocks (palm, rape, sunflower) as 1G biodiesel but hydrotreats them rather than esterifies them
  - WTT GHG depends strongly on feedstock oil and the fate of by-products of the base oil production (CH_4, plant meal, glycerin). The newest HVO plant in Europe (Rotterdam) is designed to take a wide variety of feedstock oils. Coupled with UK RFA expected feedstock split, this gives:
    - Ave. WTT GHG = -38.5 gCO2eg/MJf
  - This corresponds to **WTT CO_2 saving of 379%**

Source: UK RFA

WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX)

Average WTT CO_2 emissions for bioethanol and Bio-DME were used in this study

WTT

- **Bioethanol (E95):**
  - Bioethanol is primarily sourced from sugar cane, grain/corn/straw or forestry waste. WTT CO_2 strongly depends on which of these feedstocks are used and the fate of by-products. The CONCAWE Appendix details 5 main pathways (SBET, WTET, STET, WWET, WFET). UK RFA expects UK bioethanol feedstock split to be primarily sugar cane, with some sugar beet, wheat and corn. (The balance 5% combustion enhancer is assumed to have WTT behaviour of fossil diesel):
    - Average WTT based on expected feedstock split and E95 blend ratio GHG = -41.7 gCO2eg/MJf
  - This corresponds to **WTT CO_2 saving of 402%**
- **Bio-DME**
  - Bio DME can be sourced with a favourable CO_2 level from forestry waste, although it can also be made from fossil sources
  - CONCAWE pathways are:
    - WWDE Woodwaste WTT GHG = -62.7gCO2eq/MJf
    - WFDE Farm wood WTT GHG = -60.8gCO2eq/MJf
    - BLDE Black liquor WTT GHG = - -65.1gCO2eq/MJf
  - All three are close in WTT performance and it is difficult to identify the most prevalent pathway
  - An average WTT value of –62.9 gCO2eq/MJf is therefore used
  - corresponds to a **WTT CO_2 saving over diesel baseline of 555%**

Source: UK RFA

WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX)

There are a wide range of potential pathways for biomethane, the main UK pathways are not covered by CONCAWE

WTT

- **Biomethane**
  - Because compressed biomethane gas (CBG) is a likely substitutional biofuel for the bus market, further research has been performed to identify the most likely pathway for the UK
  - Within the CONCAWE Appendix 5 pathways are identified, all assume CBG injected to the grid:

OWCG1 (municipal waste to CBG)	WTT GHG = -39.5 gCO2eq/MJf
OWGC2 (liquid manure to CBG)	WTT GHG = -140.6 gCO2eq/MJf
OWGC3 (dry manure to CBG)	WTT GHG = -54.9 gCO2eq/MJf
OWCG4 (whole wheat plant to CBG)	WTT GHG = -34.8 gCO2eq/MJf
OWCG5 (double cropped maize + barley to CBG)	WTT GHG = -31.5 gCO2eq/MJf

  - Liquid manure utilization gets a large credit for taking otherwise lost CH_4 emissions
  - In the UK there are currently two main models envisaged for CBG production as a transport fuel
    - Gas Bus Alliance process, AD plants consuming a range of agri-waste, CBG grid injected
    - Gasrec process, AD plants or landfill, LBM delivered by tanker
  - Unfortunately neither of these exactly coincide with pathways identified by CONCAWE.
    - For the GBA-advocated approach, because of the feedstocks used, it is logical to average OWGC2, OWGC3 & OWGC5, giving -75.7 gCO2eq/MJ, **saving 576% wrt. Diesel B5%**
    - For Gasrec (landfill-biomethane-LBG) a figure of -32.7 gCO2/MJ applies (made up of the gas production part of OWCG1, the liquefaction & trucking parts of GRCG2), **saving 648%**

Source: discussions with GBA and LCVP., Gasrec website, CONCAWE Appendix

WTT CO_2 emissions for hydrogen vary depending on production process

WTT

- **Renewable Hydrogen**
  - Although not strictly a “bio” fuel, when burned as a gaseous fuel in an ICE and derived from renewable sources hydrogen exhibits similar characteristics to a biomethane (low WTT CO_2 and gaseous at point of use)
  - Transitional hydrogen derived from industrial (steam reforming) sources has high WTT CO_2 99.7 gCO2/MJ
  - Various estimates exist for the “best” and “worst” case, practical renewable hydrogen pathways:
    - From CONCAWE, the best performing H2 pathway is nuclear power generation with onsite electrolysis NUEL/CH1 7gCO2/MJ
    - Worst case is farmed wood conventional power plant onsite electrolysis 29.9gCO2/MJ
  - Renewable pathways have a range of benefit relative to diesel, **saving -88% (WTT penalty) to +56% wrt. Diesel B5%**

Source: discussions with GBA and LCVP., Gasrec website, CONCAWE Appendix

Contents

This section considers the use of fossil CNG and biomethane as a fuel for buses in the UK

Source	Liquid fuels		Gaseous fuels		
	Diesel-like fuel	Other liquid fuels	Methane	Propane	Hydrogen*
Fossil	EN590 road diesel*	DME***	CNG	LPG	Industrial (steam reformed) H2
	Coal to liquid **(CTL)		LNG		
	Gas to liquid **(GTL)				
Bio	HVO	Bioethanol	Biomethane		Renewable H2
	2G bio (BTL)	Bio DME			
	1G bio (FAME)*	Biomethanol			

Spark ignited or dual fuel engines with fuel handling system

- In buses (and HGVs) methane is generally burned in dedicated spark ignited engines derived from similar swept volume diesel engine designs.
  - The same technology is used for consuming biomethane

Natural gas can be stored on the vehicle in either liquid (LNG) or gaseous (CNG) form, buses are expected to use predominantly CNG

TTW

Natural gas distribution

- CNG:
  - Gas is delivered by the gas distribution grid, gas is compressed to the required pressure, ready for fuelling onto the vehicle (typically stored at 200–248 bar (2900–3600 psi)
- LNG:
  - At a centralised depot the gas is condensed into a liquid at close to atmospheric pressure (maximum transport pressure set at around 25 kPa/3.6 psi) by cooling it to approximately −162 °C (−260 °F) and transported by cryogenic tanker to the refuelling point

Natural gas on board storage

- The prime route expected for UK bus onboard storage is CNG, because of the complexity of onboard cryogenic fuel tanks required for LNG
- There is an increasing trend towards LNG for long haul trucks due to the increased range that this technology enables
- Buses are expected to use mainly CNG because the captive duty cycles reduce the need for a extended range
- Hence fuel distributed to the refuelling point as LNG is generally gasified (“boiled off”) to generate gaseous fuel for compression into the vehicle fuel tank.

There are a number of natural gas engine technologies, not all of which are suitable for urban buses

Stoichiometric spark ignited

- SI engine with stoichiometric air/fuel ratio
- CNG or LNG fuelling
- Light duty bifuel SI engines are fuelled by *either* gasoline *or* natural gas
- Heavy duty SI engines run *only* on natural gas

Lean burn spark ignited

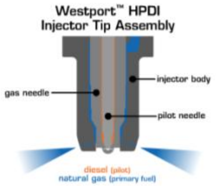
- SI engine with lean air/fuel ratio
- Port/manifold/intake fuel injection(PFI)
- CNG or LNG fuelling
- Some engines run mixed – mode lean burn and stoichiometric (these engines can use Three Way Catalyst at Euro V)
- Heavy duty SI engines run *only* on natural gas

Dual fuel diesel pilot

- Diesel injection used to ignite natural gas
- Diesel/gas substitution ratio varies with engine load and speed
- CNG or LNG fuelling
- **Current systems have low gas substitution ratio at urban bus speeds/loads and are therefore excluded from this study**

Lean diesel pilot

- Diesel injection used to ignite natural gas
- Gas injected directly into cylinder using combined diesel/gas injector (High Pressure Direct Injection)
- Gas:diesel split of 95:5, roughly constant
- LNG fuelling



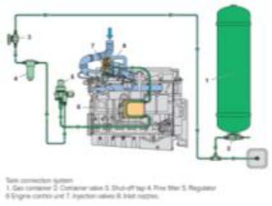
- *Stoichiometric (λ=1) combustion – exactly the required amount of air to burn the available fuel*
- *Lean (λ>1) combustion – more air than is required to burn the available fuel*

There are a wide range of CNG engines on the market

TTW

Dedicated OEM gas engines (examples)

- MAN Lion's City
  - Engine E0836/E2876, MPI, SI, EGR, TWC, lean/stoich mixed mode
- Volvo 9700
  - Engine G9B300, MPI, SI, EGR, TWC
- Cummins Westport
  - B Gas Plus: SI, lean burn
  - ISL G: SI, stoich EGR (n/a in bus ratings)
- Dedicated SI engines can be retrofitted by re-engining the bus using an existing OEM engine



Dual fuel OEM gas engines (examples)

- Lean Diesel pilot
  - Westport offer a lean Diesel pilot engine
    - High pressure direct injection (HPDI)
  - This technology is currently only offered in a 15L engine by Westport
- Dual fuel Diesel pilot engines are offered by a number of manufacturers
  - Volvo offers this technology on their FM MethaneDiesel truck
  - The market is currently dominated by retrofits from a number of manufacturers (for example, Clean Air Power, Hardstaff)
  - Diesel pilot systems retain diesel-like fuel consumption (BSFC) at full load but have degraded BSFC at part load (~+50% at mid) so would not be expected to give benefits for a largely low load urban bus cycles and are therefore excluded

Source: Ricardo analysis and data

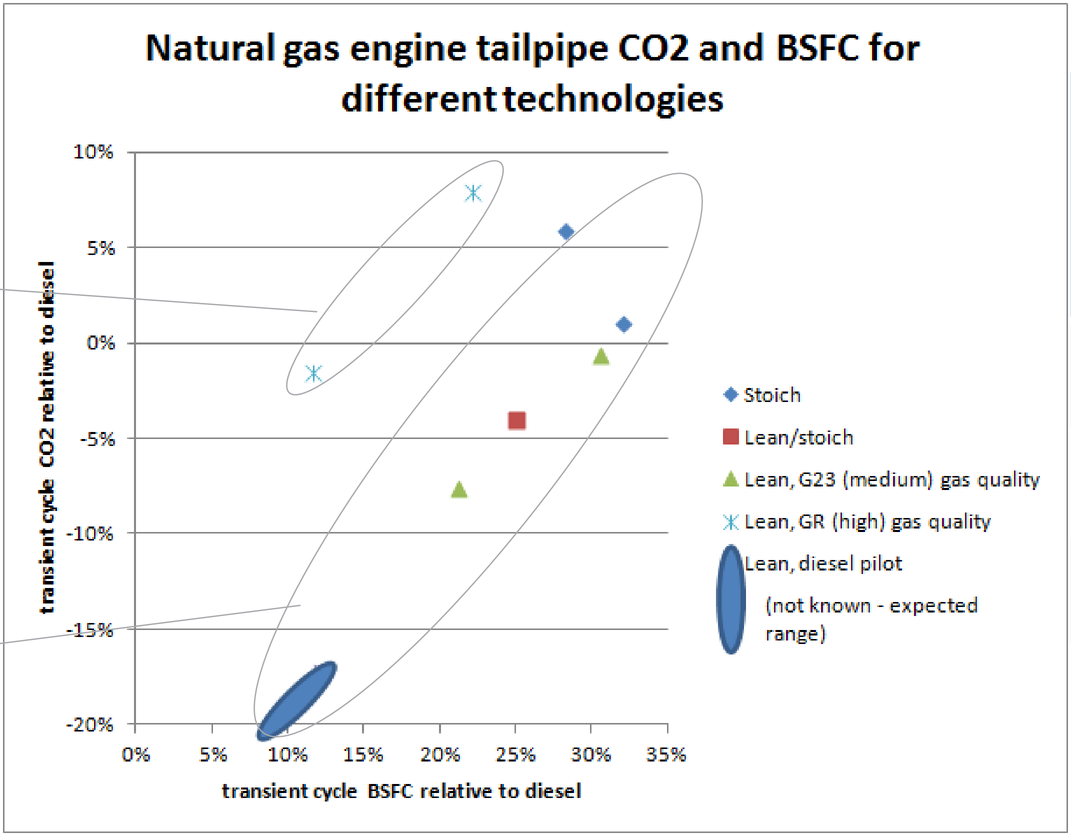
Gas quality and engine technology affect fuel consumption and therefore tailpipe (TTW) CO_2 emissions for CNG engines

TTW

- The plot below shows TTW CO_2 performance of OEM SI gas engines over transient emissions test cycles, which varies widely and depends mainly on two factors:
  - Fuel efficiency/BSFC of the combustion technology applied to the engine
  - Quality of the gas used (inert content, density, calorific value)

High (atypical) gas quality (high density & CV, low inert, high availability of C atoms)

Typical “real” gas quality (lower density & CV, higher inert, lower availability of C atoms)

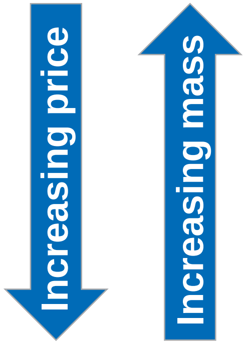


Technology	Engine out CO_2 % change used in this study (-ve is better than Diesel)
Stoich SI	+4%
Lean SI	-1%
Lean diesel pilot LNG*	-18%

* Lean Diesel pilot only currently offered by Westport on non-bus sized engine

Source: Ricardo analysis and data

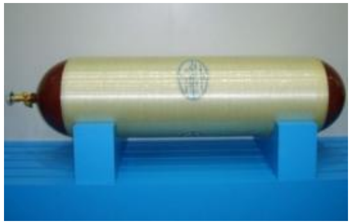
There are a number of CNG tank configurations on the market, configuration selection depends on the application


Increasing price

Increasing mass

- **There are 4 types of cylinder in use for storing compressed natural gas**
  - Type 1: All metal cylinder made of steel or aluminium
  - Type 2: Metallic cylinder with a partial hoop wrapping made with glass fibre or carbon fibre
  - Type 3: Metallic cylinder is fully wrapped by glass fibre or carbon fibre
  - Type 4: Plastic gas-tight liner reinforced by composite wrap around entire tank


Type 1


Type 2


Type 3

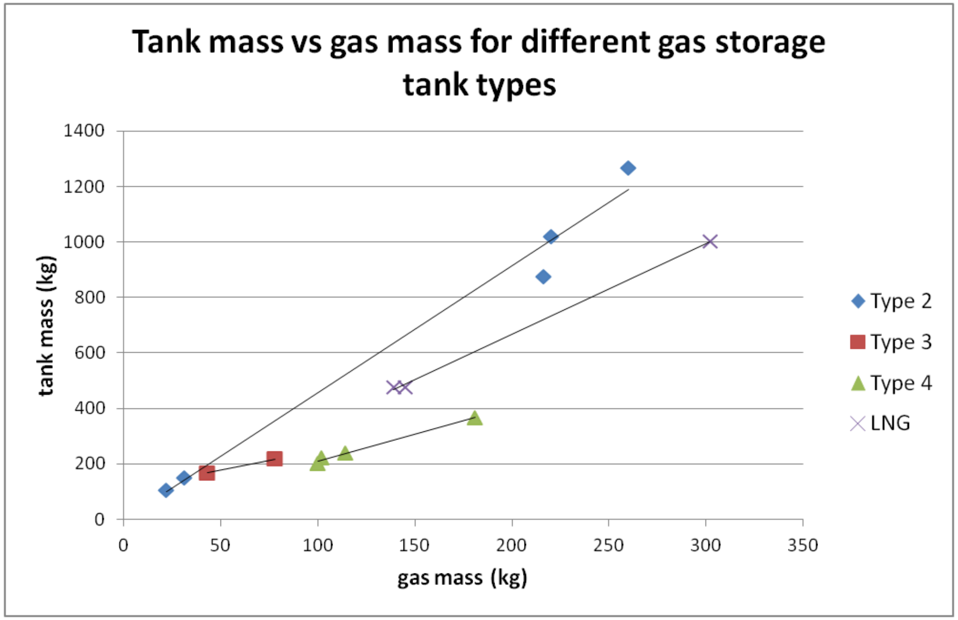

Type 4

- Light duty vehicles tend to store CNG at 200 bar, buses and trucks at 250 bar
- Tank type selected depends on the application, typical tank selections are:
  - Passenger car and bus applications - Type 2 tanks for low cost
  - LCV applications - Type 3 tanks
  - Heavy Duty applications - Type 4 tanks to maximise payload

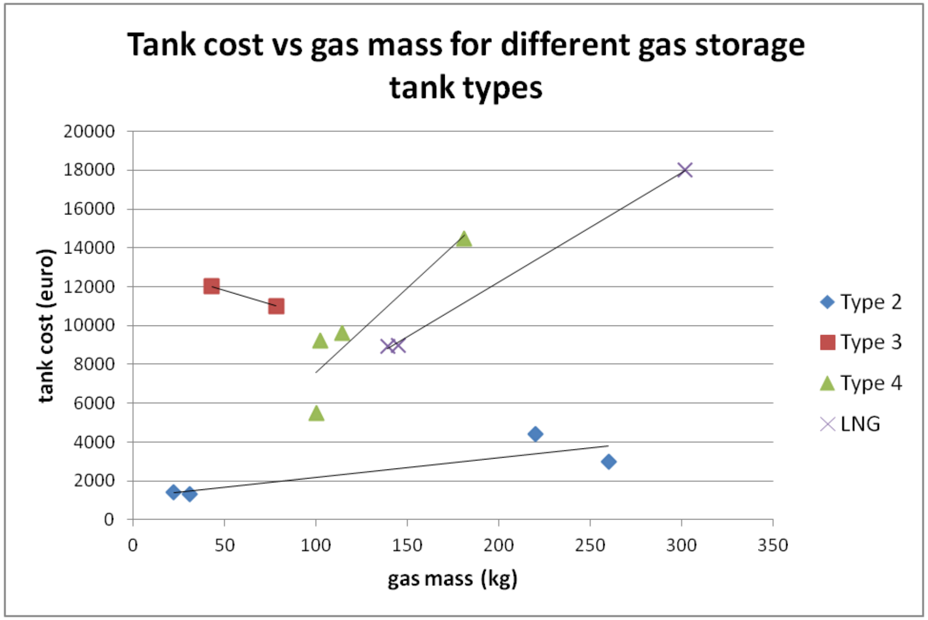
Source: Ricardo analysis and data

The type of tank selected has a significant effect on storage mass and cost – current CNG buses typically have Type 2 tanks

- Gas buses on the market in both Europe and US typically have Type 2 tanks
- Graphs on this slide show the variation of tank mass and cost with gas mass for different tank types
- A move to Type 4 tanks would reduce mass, but with a significant increase in cost



- Type 4 tanks are generally confined to use on HD trucks where weight saved on tank mass can be used for additional payload
- This study assumes that a Type 2 CNG tank sized for 300 miles range is used, weighing 500kg



Source: Ricardo analysis and data

Finally WTT characteristics for fossil-based CNG pathways should be considered

WTT

- The following pathways are considered in the CONCAWE study:
  - EU mix NG supply (i.e. how the EU gets its gas at the current time)
  - Piped NG (7000km) to CNG – gas imported into the EU through pipelines from Western Siberia (main current and future supply)
  - Piped NG (4000km) to CNG – gas imported into the EU through pipelines from East of South Western Asia (key regions for future EU supplies)
  - LNG to CNG – LNG imported in the EU from remote sources (e.g. the Middle East) by ship. LNG is vaporised into the EU gas grid. An option is included where CO_2 produced in the liquefaction site power plant can be captured and injected back into the gas/oil field
  - The above three are considered by CONCAWE the most likely marginal gas supply routes to the EU
    - Marginal supply – the increased supply required to deal with an incremental increase in demand (e.g. in this case, an increased demand for gas as a road fuel)

Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX)

WTT CO_2 emissions for fossil CNG pathways vary depending on the international transmission route

WTT

- CONCAWE analysis of WTT GHG emissions for EU pathways is as follows:
  - GMCG1 (EU mix NG supply – current) WTT GHG = 8.7gCO2eq/MJf
  - GPCG1a (Piped NG (7000km) to CNG) WTT GHG = 22.3 gCO2eq/MJf
  - GPCG1b (Piped NG (4000km) to CNG) WTT GHG = 14.5gCO2eq/MJf
  - GRCG1 (LNG to CNG) WTT GHG = 20.2 gCO2eq/MJf
  - GRCG1C (LNG to CNG with CCS) WTT GHG = 16.7 gCO2eq/MJf
- It may be argued that the CONCAWE “EU average” current NG supply scenario is not applicable to UK gas which currently comes predominantly from North Sea fields
- Pipeline length from production to entry to the transmission system has a significant impact on WTT GHG emissions for gas pathways, and so it is important to understand the effective pipeline length in order to estimate the UK applicable WTT GHG signature, if deviation from the established CONCAWE EU estimates is to be justifiable
- This has been estimated overleaf, but an exhaustive study is outside the scope of this project and it is recommended to more closely examine UK-specific gas pathway WTT emissions if CNG or LNG is to be strongly promoted as a low carbon technology

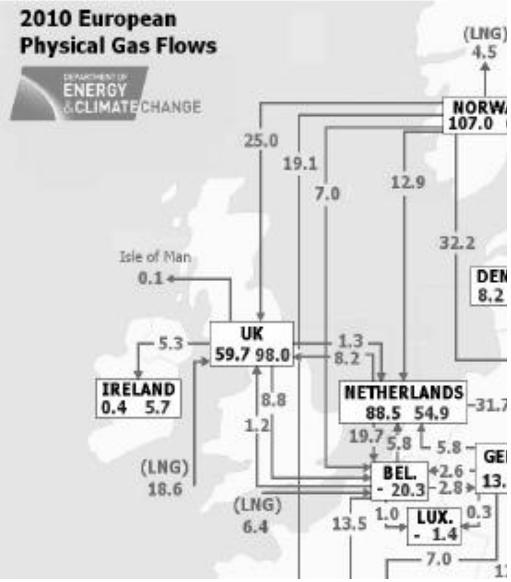
Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX),

WTT CO_2 emissions for fossil CNG pathways vary depending on the international transmission route

WTT

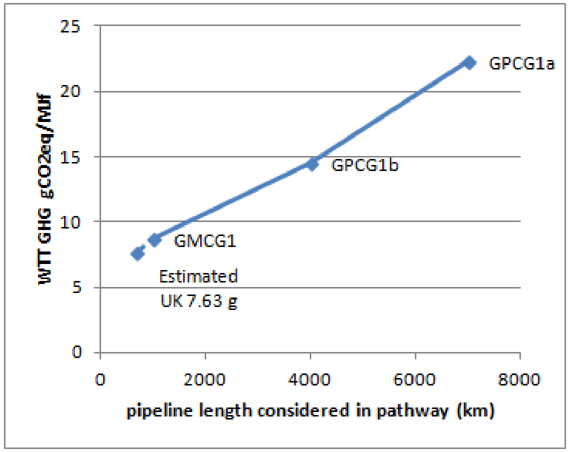
- UK gas currently comes predominantly from North Sea fields with a typical pipeline length as follows:

Source	Capacity (b m³)	Length (km)
UK North sea	[1]550TWh = 50	500 (estd)[1]
Norway Sleipner Langeled	[2]25.5	1166
Norway Heimdal Vesterled	[3]12	360
Capacity weighted average		675



Map 4.2: The National Gas Transmission System 2011

Source: International Energy Agency and DECC

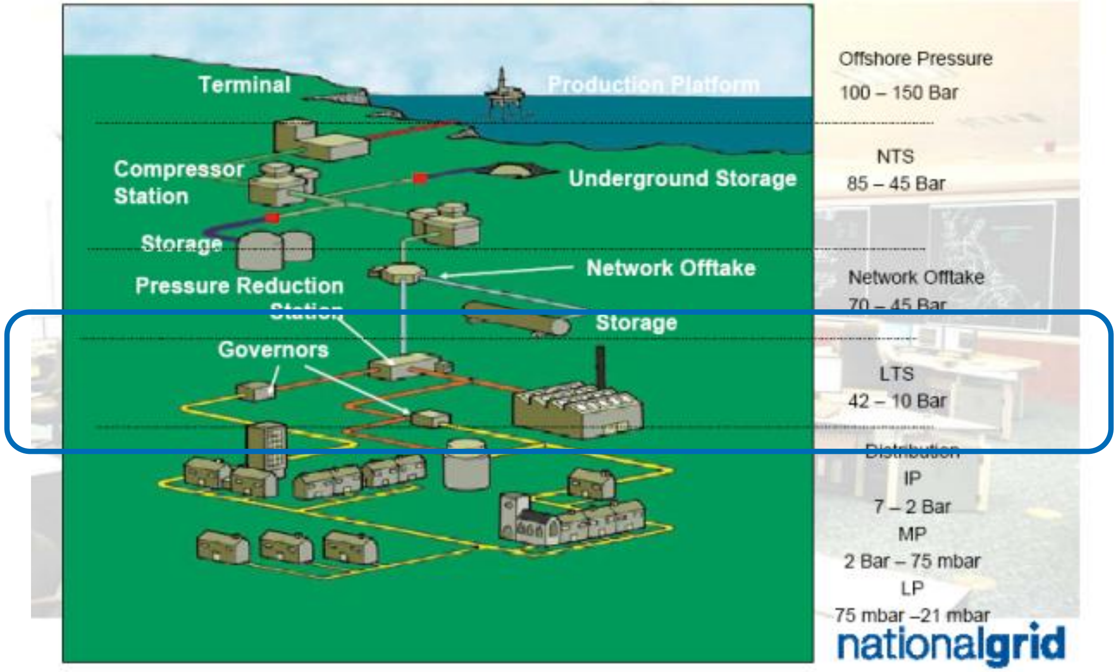


- Extrapolating CONCAWE WTT GHG figures for 3 different pipeline lengths back to a UK-typical length of 675km gives an **estimated UK-typical WTT GHG emission of 7.6gCO2eq/MJf** (compare 8.7gCO2eq/MJf for CONCAWE EU current)

Source: [1]DUKES, Wikipedia '[3]Vesterled, [2]Langeled'; CONCAWE WTT

WTT CO_2 emissions for fossil CNG pathways also vary depending on the local transmission & distribution method

- For example, transport refuelling from the Local Transmission System (LTS) or Local High Pressure (LHP) mains, rather than the distribution system, reduces the need to compress and dry CNG before vehicle use – lowering TTW CO_2 emissions for transport fuel CNG
  - This reduction has been estimated to be around 1.9 g CO_2/MJf by Joules Vert, based on the reduction of CO_2 emissions from values reported by CONCAWE/JEC
- The useability of the LTS depends on the proximity of the refuelling infrastructure to it
  - A detailed assessment is necessary for each refuelling station to evaluate the potential to use the LTS
  - Some local schemes currently transport CNG from the LTS to a nearby refuelling station at approaching LTS pressure
  - A detailed analysis of proximity of LTS to bus depots using National Grid MAPS data is beyond the scope of this study, but an initial search shows LTS nodes are often outside urban areas or in rural areas
  - It is unlikely therefore that a large proportion of bus refuelling facilities could use the LTS - and hence take advantage of this CO_2 reduction – without further investment

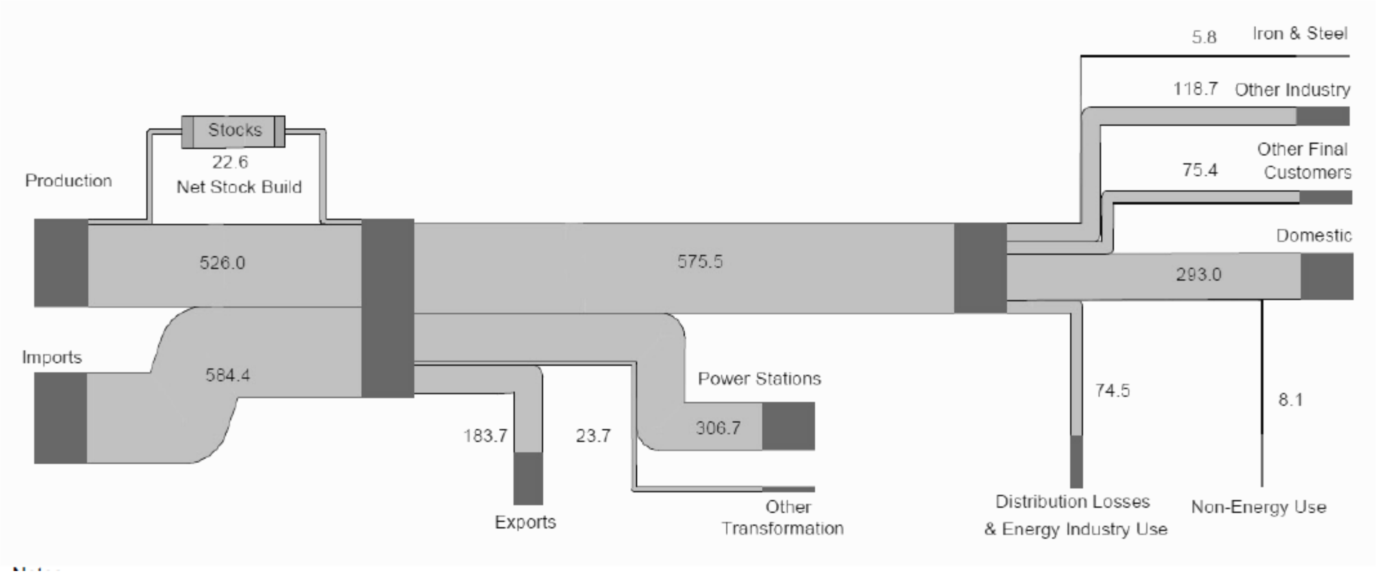


Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX), National grid/GL Noble Denton MAPS, JoulesVert

A range of scenarios are considered for UK natural gas supply including CONCAWE marginal supply

- Road transport currently accounts for 37.2MTOE energy use in the UK (2010 figures from DUKES/DECC) where 1TOE is equivalent to 42GJ or 11630kWh
  - Total road transport energy use is equivalent to 1.6EJ or 433TWh
- If 5% of road transport switched to gas, this 22TWh would represent a 4% increase in non-power station gas demand
  - Consideration of marginal supplies would be important if such a switch occurred

Natural gas flow chart 2011 (TWh)



Source: DfT Statistics ENV0102 ; Digest of UK Energy Sources (DUKES) 2012 Chapter 4

WTT CO_2 emissions must be calculated on a CO2eq basis capturing methane emissions from production

WTT

- It is important to note that each of the CONCAWE gas pathways includes a significant (in GWP terms) contribution from methane leaks (fugitive methane) during the gas production process Therefore when considering methane fuels it is vital to ensure that GHG emissions as a whole (in CO_2 **equivalent** term) are considered, not just raw CO_2 emissions
- Examples of transmission, storage and distribution (TS&D) network activities contributing to fugitive CH_4 emissions (from “Life-Cycle Analysis of Shale Gas and Natural Gas” Argonne National Lab,
  - Processing/Transmission/Storage:
    - Acid gas removal, Blowdowns/venting, Recip/centrifugal compressors, Dehydrators, Pneumatic devices
  - Distribution:
    - Mileage of mains/services and material (iron, copper, plastic), Pressure regulation, Customer metering
- Argonne estimated fugitive CH_4 emissions were 0.3%(v/v) of total US NG production
- Analysis is further complicated by change in GWP depending on the timescale considered (GWP_{20} – 20 year timeframe versus GWP_{100} – 100 year). CONCAWE uses GWP_{100}
- This translates to TS&D fugitive CH_4 contributing 7% of GWP_{20} and 2% of GWP_{100} for CNG , on a gCO2e/MJ basis, but with a GWP_{100} of 23 this equates to 32% of the total GWP_{100} of the process

Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX) http://greet.es.anl.gov/files/shale_gas Dec 2011).

A range of WTT CO_2 emissions for fossil CNG are possible for the UK, depending on the distribution and transmission method

WTT

- Adding the additional estimated UK-specific WTT pathways to the CONCAWE EU and re-ordering by WTT GHG emissions:

– GPCG1a (Piped NG (7000km) to CNG)	WTT GHG = 22.3 gCO2eq/MJf
– GRCG1 (LNG to CNG)	WTT GHG = 20.2 gCO2eq/MJf
– GRCG1C (LNG to CNG with CCS)	WTT GHG = 16.7 gCO2eq/MJf
– GPCG1b (Piped NG (4000km) to CNG)	WTT GHG = 14.5gCO2eq/MJf
– GMCG1 (EU mix NG supply – current)	WTT GHG = 8.7gCO2eq/MJf
– UK current mix NG supply estimate	WTT GHG = 7.6gCO2eq/MJf
– UK current mix NG, fuelling using LTS	WTT GHG = 5.7gCO2eq/MJf

- Two scenarios are then considered: best possible UK supply and marginal supply
- **Best UK supply -** Best current (ignoring future demands) UK natural gas WTT GHG emissions assumes that estimated UK supply is delivered via the LTS. Achieving this would require investment in LTS based refuelling. A WTT value of 5.7gCO2eq/MJf is assumed. **This corresponds with a WTT benefit of +59% wrt. Baseline Diesel fuel (B5%)**
- **Marginal supply** - Since it is difficult to predict the most likely pathway for future marginal supply, it is assumed that the reality will be a mixture of all and hence for marginal future gas supply an average WTT value of 18.4gCO2eq/MJf is assumed. **This corresponds with a WTT penalty of -33% wrt. Baseline Diesel fuel (B5%)**

Source: WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX)
Ricardo analysis,

WTT CO_2 emissions for fossil CNG pathways for the UK have a wide variation depending on assumptions made

WTT

- WTT CO_2 values have been estimated as described previously, for a number of different distribution scenarios

CNG pathway	Fuel WTT CO_2 (g CO2eq/MJ)
UK mix (likely current)	7.6
UK mix w. LTS fuelling (possible best)	5.7
Marginal supply average (possible future)	18.4
Diesel (CONCAWE COD1)	13.8

Range considered in this study

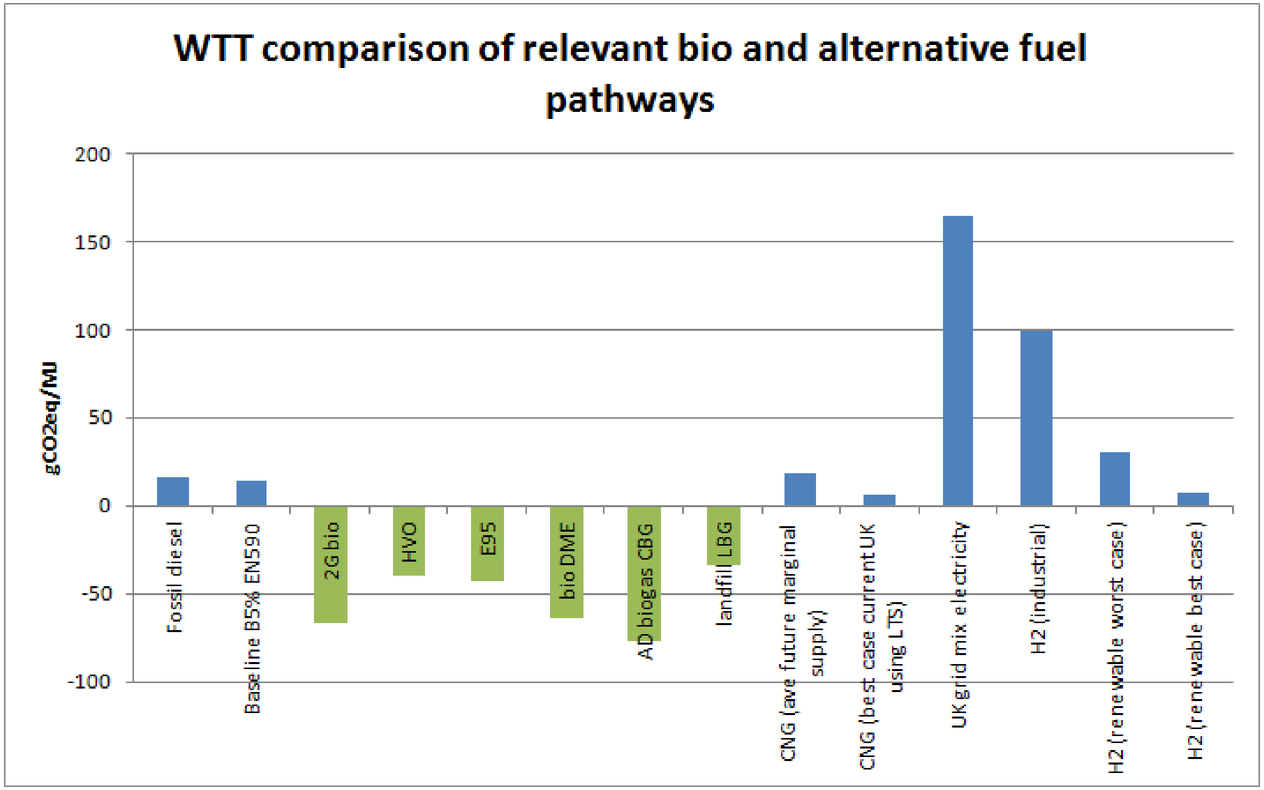
- This analysis shows a range of scenarios for WTT CO_2 emissions for fossil CNG:
  - If a small number of CNG buses (and other transport consumers) are on the road, then existing supply (UK mix) can be assumed at least for the near future – TTW CO_2 emissions are better than diesel
  - If a small number of CNG buses are on the road **and** investment takes place to allow the LTS grid to be used to fuel the buses then a greater TTW CO_2 benefit over diesel can be assumed
  - If a significant shift to natural gas use for transport occurs – i.e. buses and transport consumers are fuelled using marginal supply remote from the UK – then a sizeable TTW CO_2 penalty over diesel could result

Source: Ricardo Analysis, CONCAWE

Alternative fuel Well to Tank CO_2 emissions (per unit of primary energy) summary

WTT

- All “bio” pathways have negative WTT GHG emissions if CO_2 emissions which are avoided by the use of by-products is included
- WTT GHG emissions for natural gas are heavily dependent on current and future UK gas supply pathways, and cannot be assured to be lower than fossil diesel



Source: Ricardo analysis, WTW Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC (Report Version 3c APPENDIX), DEFRA

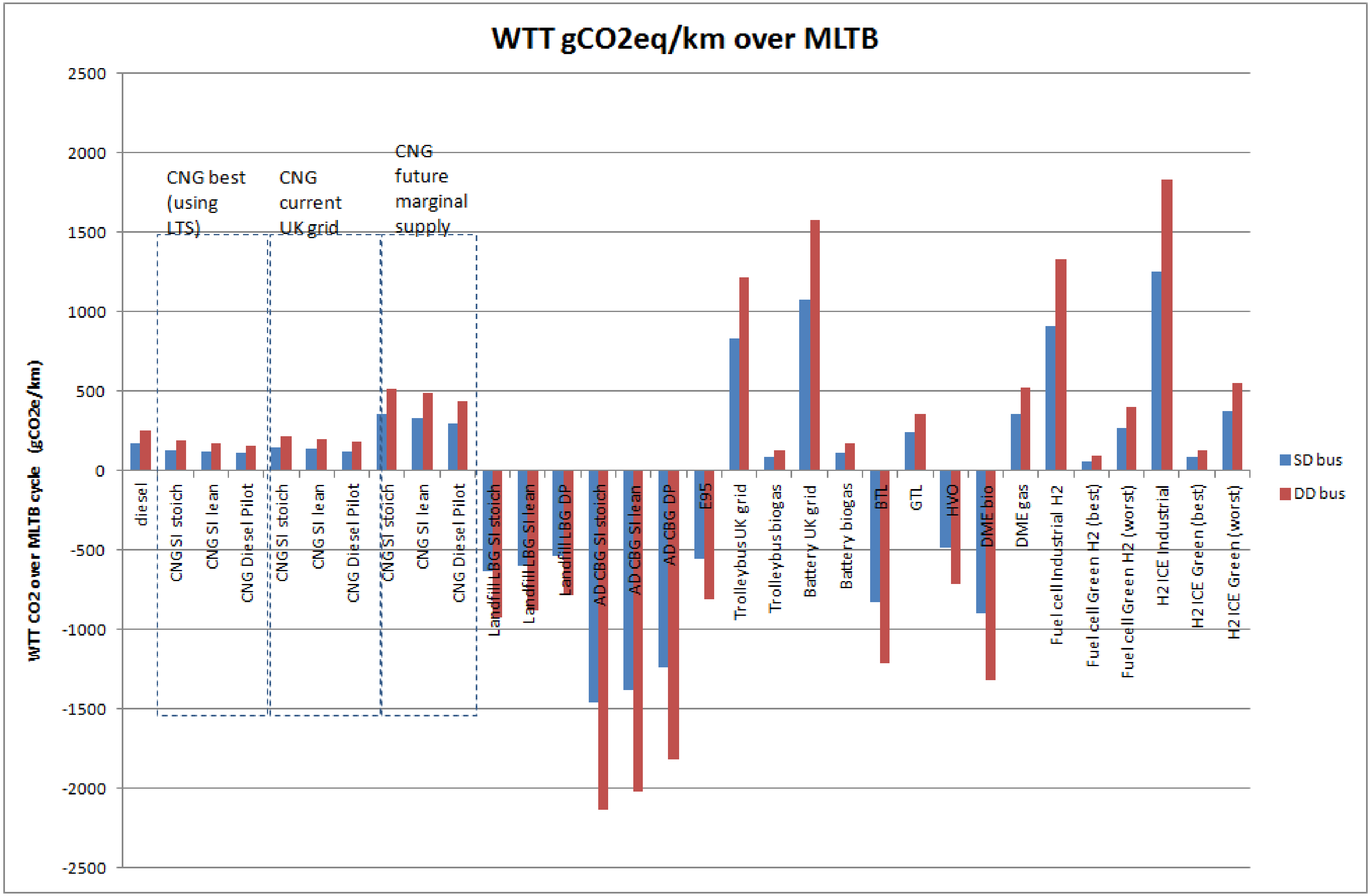
Contents

Well to wheels analysis is carried out by combining TTW emissions for bus technology with fuel WTT CO_2 emissions values

- In order to draw together the WTT and TTW contributions into a final WTW figure, for those fuels which have a WTW impact, it is necessary to:
  1. Identify the primary TTW fuel energy requirement – i.e. how much energy encapsulated in the alternative fuel is required to drive a specific route (in this case the MLTB cycle) (MJ/km)
     - Derived from cycle analysis for SD/DD bus (how much energy at the wheels is required to drive the cycle), plus consideration of the conversion efficiency of the engine when running on the particular fuel (e.g. efficiency of stoich SI engines)
  2. Identify the TTW (tailpipe) CO_2
     - Derived from quantity of fuel is burned to drive the cycle and how much CO_2 that fuel produces (carbon content of the fuel) (gCO_2eq/km)
  3. Identify the WTT CO_2
     - Take the primary TTW fuel energy from (1) above, and apply the relevant fuel pathway WTT CO_2 value (gCO_2eq/MJ)
- Then TTW and WTT can be added to give WTW in gCO_2eq/km
- The following analysis excludes impact of vehicle mass increases to accommodate the stored fuel (e.g. gas tank mass). This effect is added in the individual technology slides

WTT CO$_2$ emissions for the fuels considered in this study

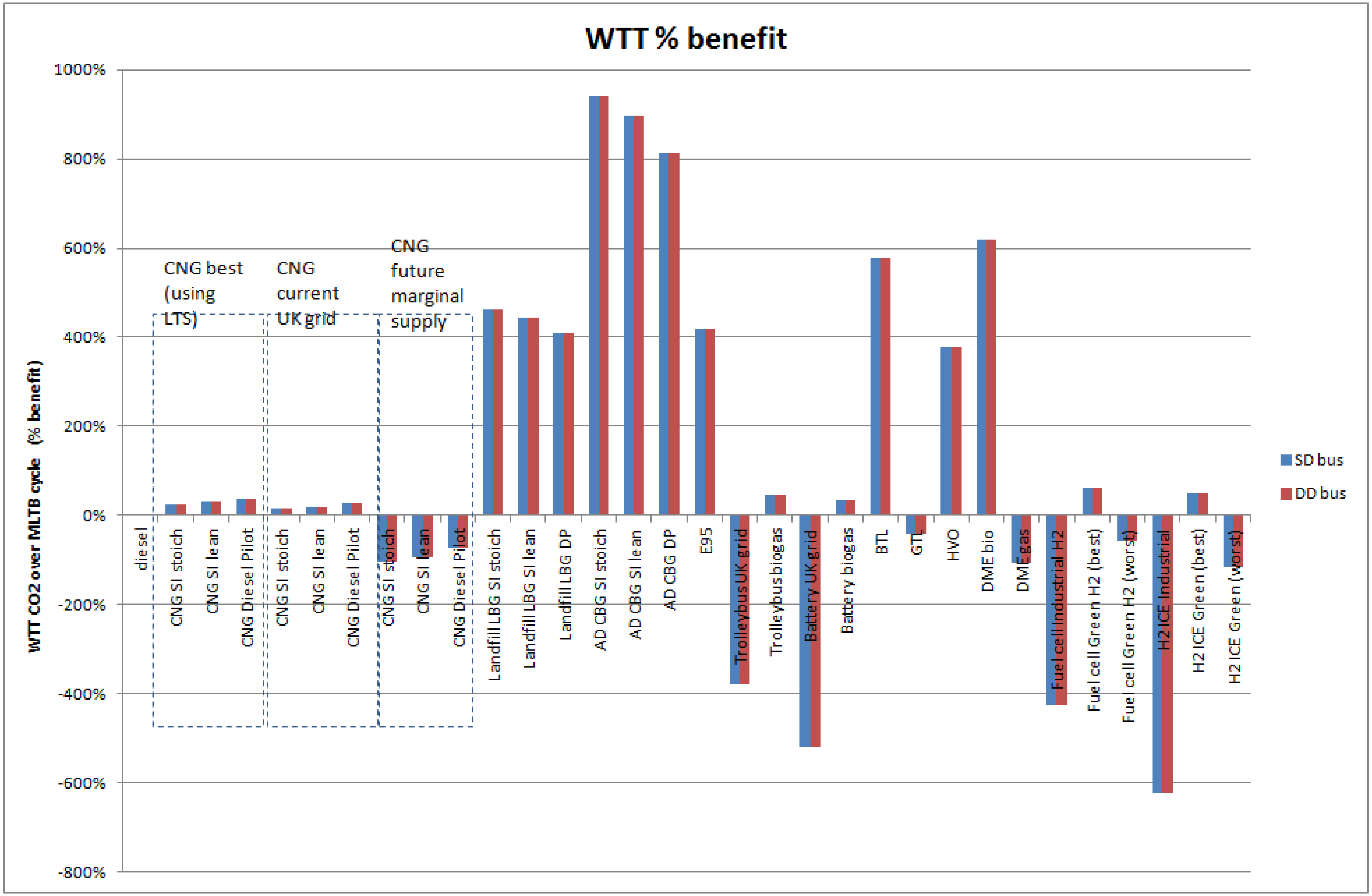
- Fuels WTT analysis (Sources in previous section)



Source: Ricardo analysis

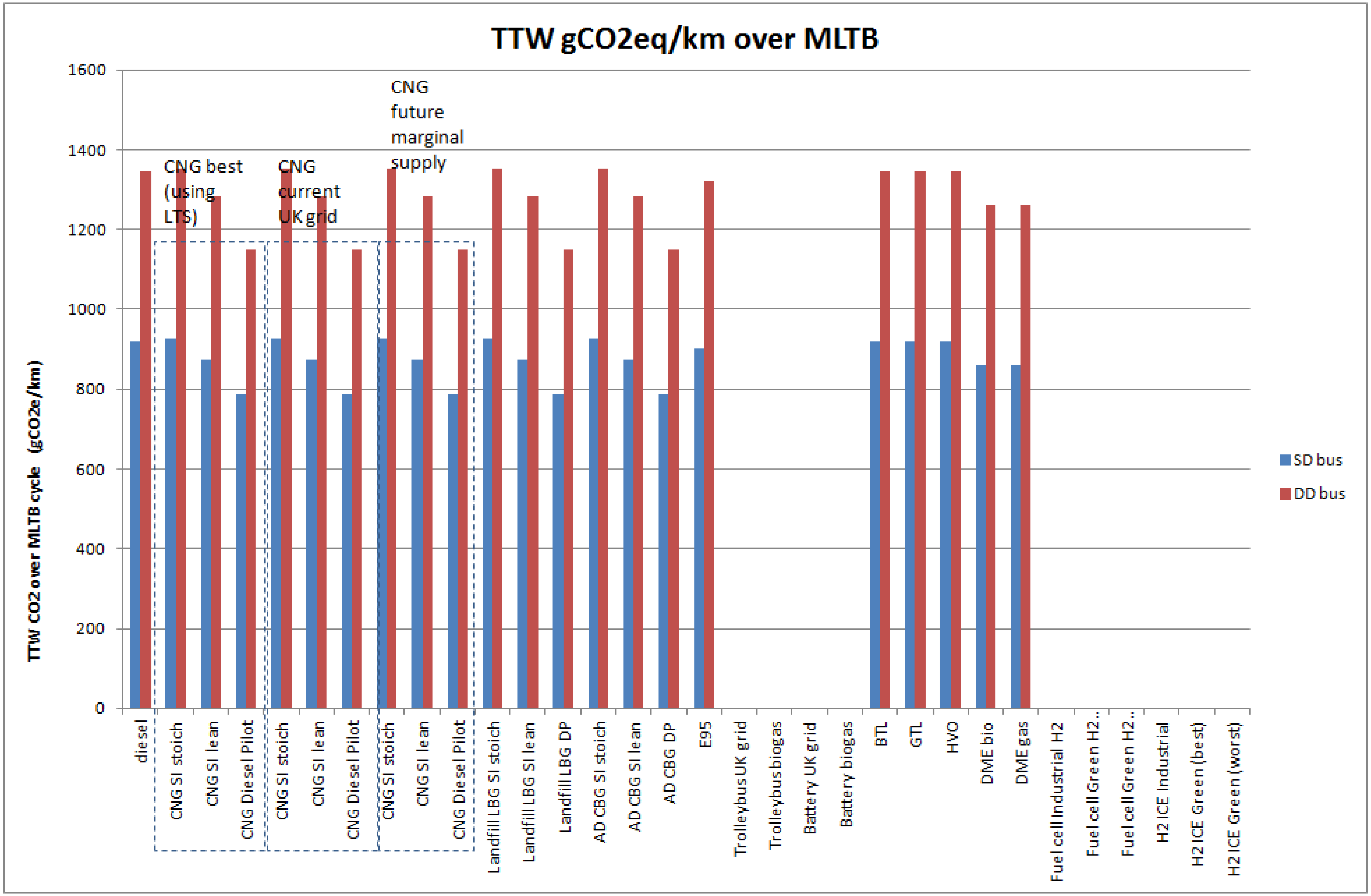
WTT CO_2 emissions expressed as a % change from diesel

- WTT in % benefit terms, % WTW is **not** equal to % WTT + % TTW



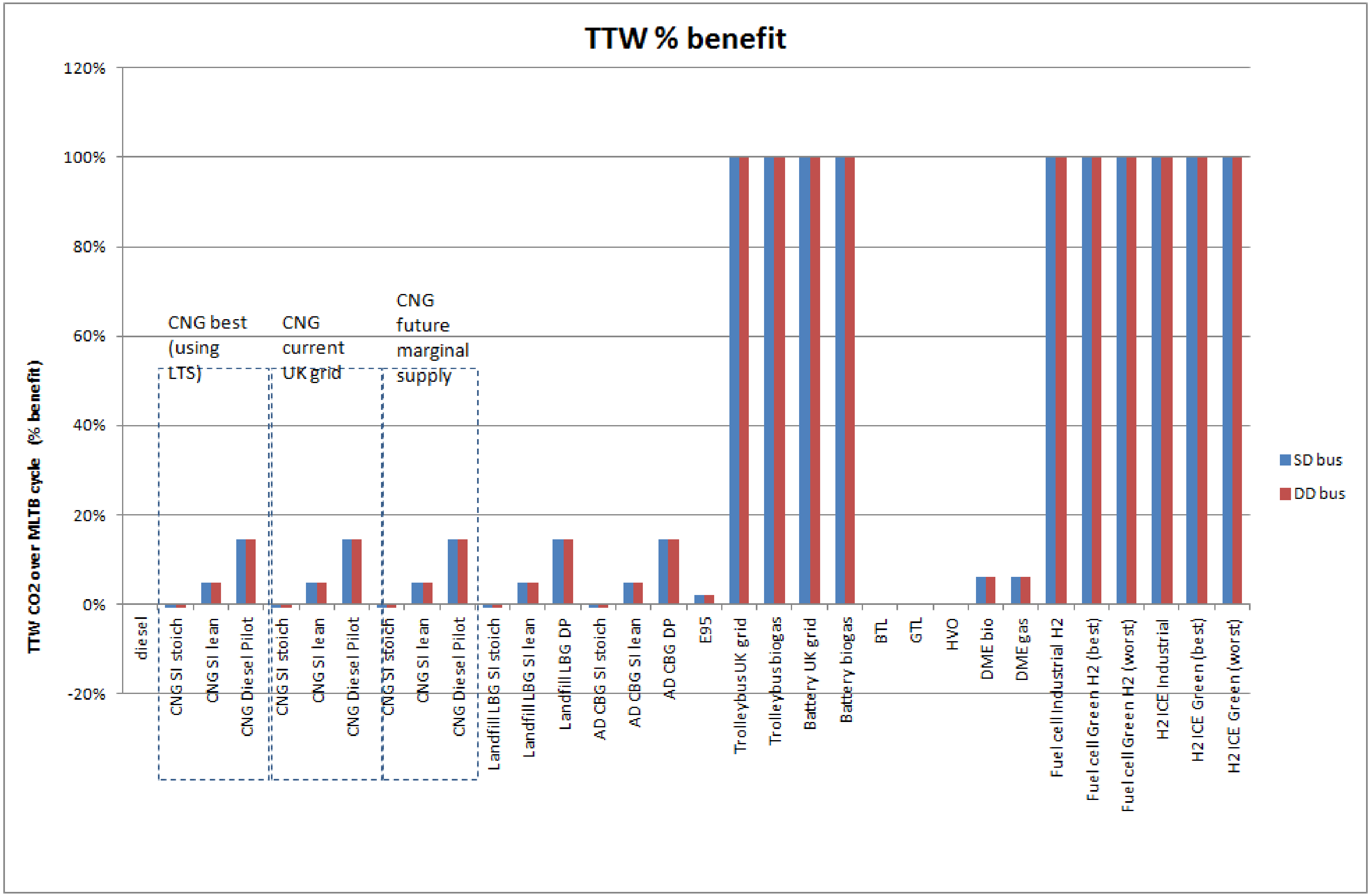
This slide shows tank to wheels CO_2 emissions for a range of fuels, based on assessment of bus fuel consumption over MLTB

- TTW analysis: based on Ricardo analysis of engine technology & fuel carbon content



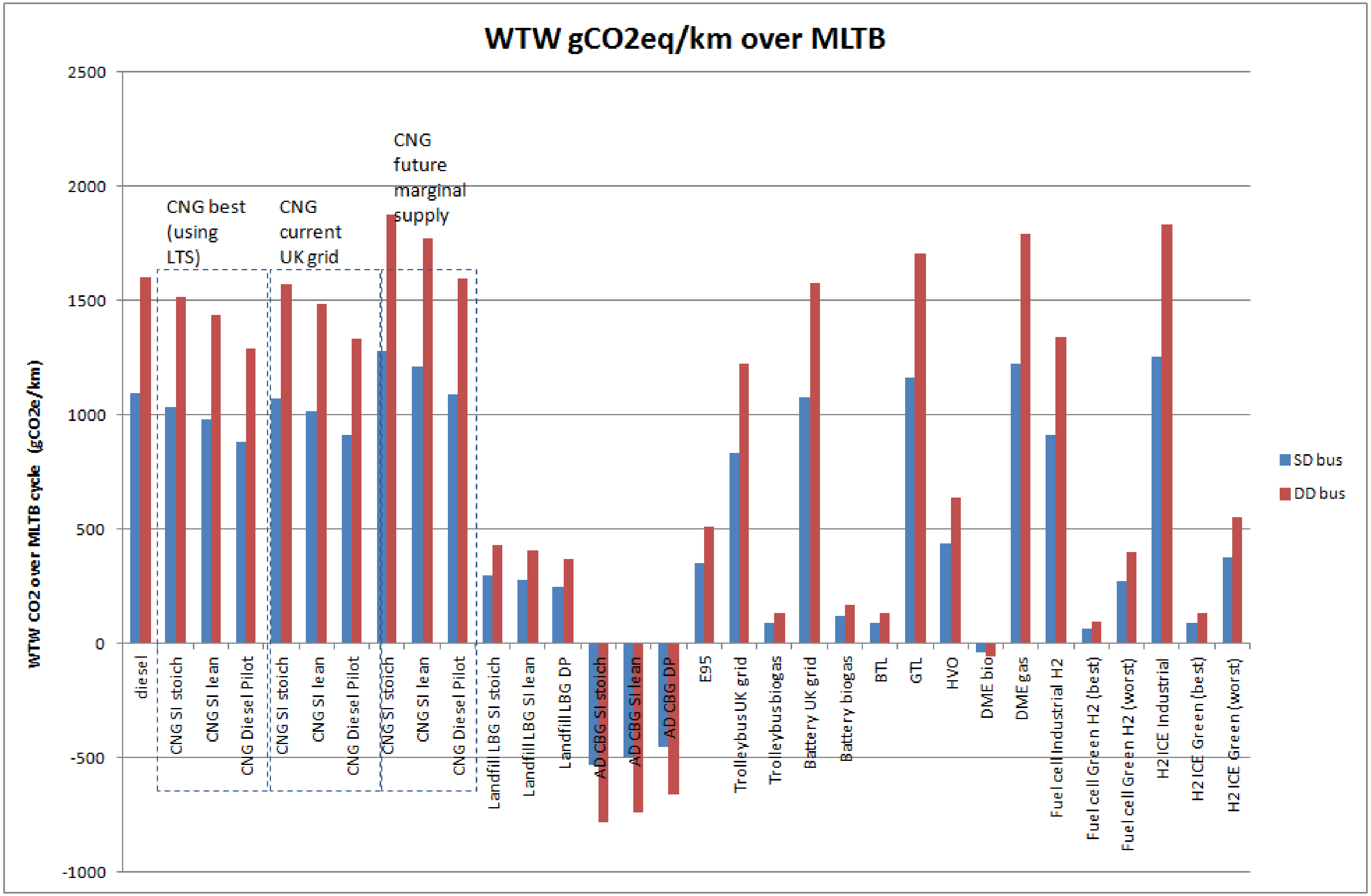
TTW benefits expressed as a % change from diesel

- Electric and hydrogen fuelled buses give zero TTW emissions



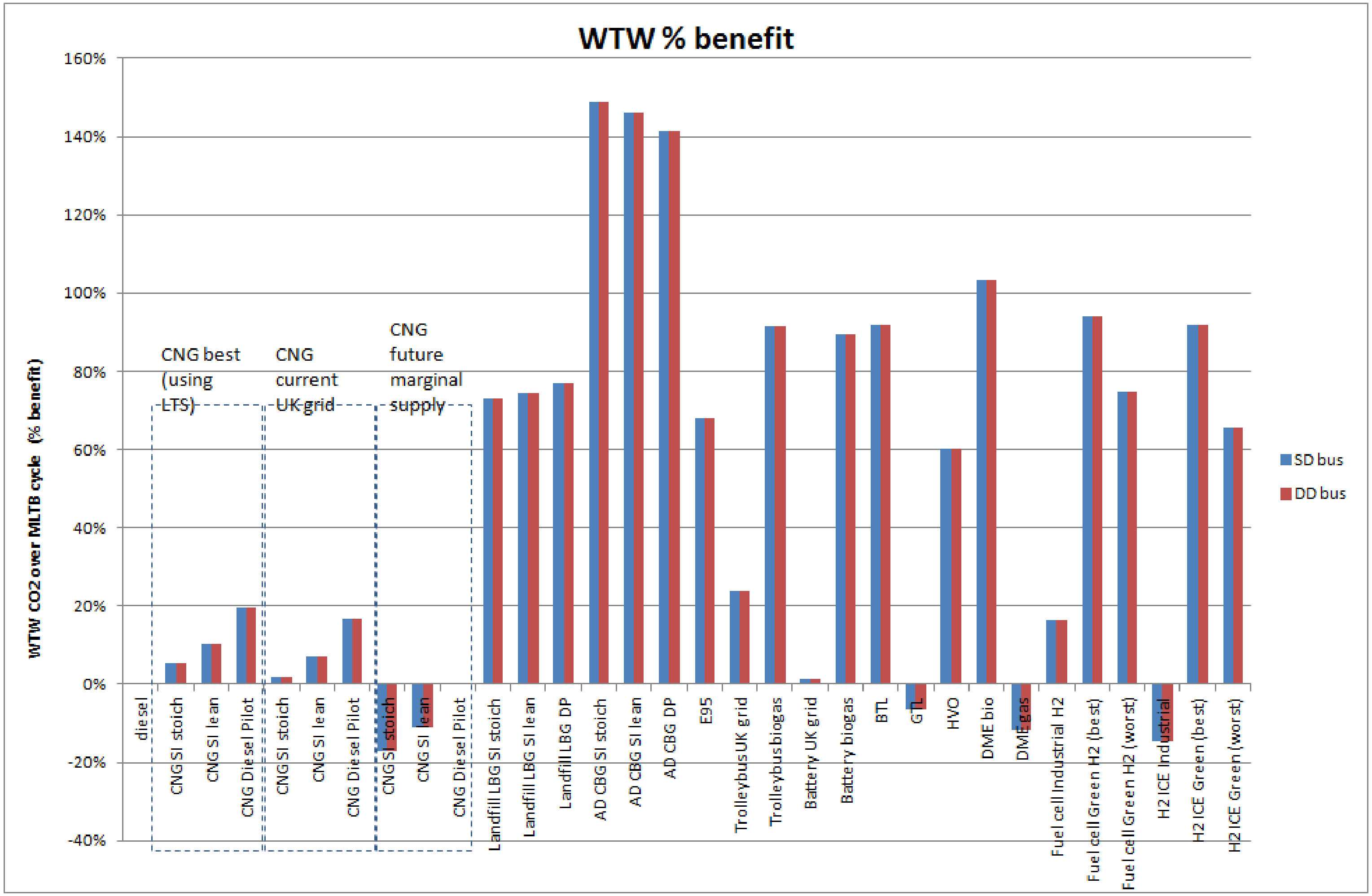
WTW CO_2 emissions in g CO_2 eq/km is the sum of WTT and TTW CO_2 emissions

- WTW: sum of WTT + TTW (in consistent units gCO2eq/km), based on energy required for MLTB



WTW performance for fuels and engine technologies can then be calculated as a % change from diesel

- Benefits from CNG and biomethane varies depending on gas pathway and engine technology
  - CNG fuelled engines can swing between better or worse CO_2 emissions compared to diesel dependent on both engine type and gas pathway



WTW CO_2 emissions for fossil CNG pathways vary between a significant increase to a small benefit for stoich CNG engines depending on the CNG pathway

WTW

- WTW CO_2 values have been calculated for stoichiometric, Lean and Diesel pilot CNG engines for a number of different distribution scenarios, shown below relative to Diesel B5 WTW emissions

CNG pathway	Fuel WTT CO_2 (g CO2eq/MJ)	Stoich engine WTW % CO_2 reduction	Lean WTW % CO_2 reduction	Diesel pilot WTW % CO_2 reduction
UK mix (likely current)	7.6	1.9	7.1	16.6
UK mix w. 100% LTS fuelling (possible best)	5.7	3.6	8.7	18.0
Marginal supply average (possible future)	18.4	-17.1	-10.9	0.5

CO_2 emissions in this table do not include the effect of tank mass

- This analysis shows the sensitivity of WTW CO_2 emissions for engines fuelled with fossil CNG:
  - If a small number of CNG buses (and other transport consumers) are on the road, then existing supply (UK mix) can be assumed – stoich engine buses are expected to be CO_2 neutral/slightly positive with Lean and Diesel pilot engines showing a greater benefit
  - If a small number of CNG buses are on the road **and** investment takes place to allow the LTS grid to be used to fuel the buses then a WTW CO_2 benefit is gained for all CNG technologies
  - If a significant shift to natural gas use for transport occurs – i.e. buses are fuelled using marginal supply remote from the UK – then a sizeable WTW CO_2 penalty could expected
- **In the remainder of the report, a range of values for WTW CO_2 reduction for fossil CNG is used to show the effect of different CNG pathways**

Source: Ricardo Analysis

Contents

HVO is an advanced 1st generation biodiesel similar to that of a fully synthetic BTL type

Hydrotreated Vegetable Oil (HVO)

- **Description:** advanced 1st generation or 1 ½ gen. biodiesel made by treating vegetable oil or animal fat with hydrogen. HVO is a synthetic diesel which can be used to fuel all diesel vehicles without modification
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: HVO is commercially available in Finland as a 10% blend in Neste Oil‘s Green Diesel therefore it is a mature technology but supply is limited; current global production equates to1% of European diesel market
- **Potential Fuel Savings and CO_2 Benefit:** no CO_2 benefit in tailpipe emissions; WTW GHG reduction for pure HVO is 60%
- **Technology Price:** HVO fuel can be used in existing engines with no additional technology required. Fuel production cost is likely to be higher than conventional diesel but price at pump expected to be equal
- **Maintenance Cost:** no other additional running costs anticipated

	SD	DD
TRL	8	8
Development to TRL 9	M	M
WTT GHG reduction (%)	60	60
Technology Price (£)	0	0
Maintenance Cost (£)	0	0

Picture Source: Neste Oil

Source: Ricardo Analysis, Neste Oil

BTL is a 2nd generation biodiesel which is currently not commercially available in significant quantities

Biomass to Liquid (BTL)

- **Description:** 2nd generation biodiesel produced by converting Biomass to Liquid (BTL). BTL is a synthetic diesel which can be used to fuel all diesel vehicles without modification
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: BTL production process under development; construction complete on beta-test production plant in Germany; available as niche fuel - current global production equates to less than 1% of european diesel market
- **Potential Fuel Savings and CO_2 Benefit:** no CO_2 benefit in tailpipe emissions; WTW GHG reduction for pure BTL is 92%
- **Technology Price:** BTL fuel can be used in existing engines with no additional technology required. Fuel production cost is likely to be higher than conventional diesel but price at pump expected to be equal
- **Maintenance Cost:** no other additional running costs anticipated

	SD	DD
TRL	8	8
Development to TRL 9	M	M
WTT GHG reduction (%)	92	92
Technology Price (£)	0	0
Maintenance Cost (£)	0	0

Picture Source: Sun Diesel, Choren

Source: Ricardo Analysis, Choren, available at: www.choren.com

Bioethanol E95 in CI Engine burns ethanol in a compression ignition engine using 5% ignition enhancer

Bioethanol E95 in CI Engine (5% Ignition Enhancer)

- **Description:** a conventional diesel engine modified to burn a blend of 95% ethanol / 5% combustion enhancer (PEG). Engines are offered from e.g. Scania and have been trialled worldwide. Engine / Fuel Injection Equipment (FIE) must be recalibrated to allow for reduced energy density
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Fleets have run in Sweden, Brazil, London and other localities
- **Potential Fuel Savings and CO_2 Benefit:** 2% reduction in tailpipe CO_2 and WTW CO_{2eq} 68% lower than diesel bus WTW CO_2
- **Technology Price:** Typically 10-15% higher price, based on BEST report. Fuel cost £/l expected comparable although highly influenced by taxation policy. Reduced energy density means that 1.42x the fuel volume needed so £/kWh cost is higher
- **Maintenance Cost:** Not expected to be higher than diesel

	SD	DD
TRL	9	9
TTW CO_2 Benefit (%)	2	2
WTT CO_2 Benefits (%)	68	68
Technology Price (£)	21,000	32,000
Maintenance Cost (£)	0	0

Picture Source: Scania ...

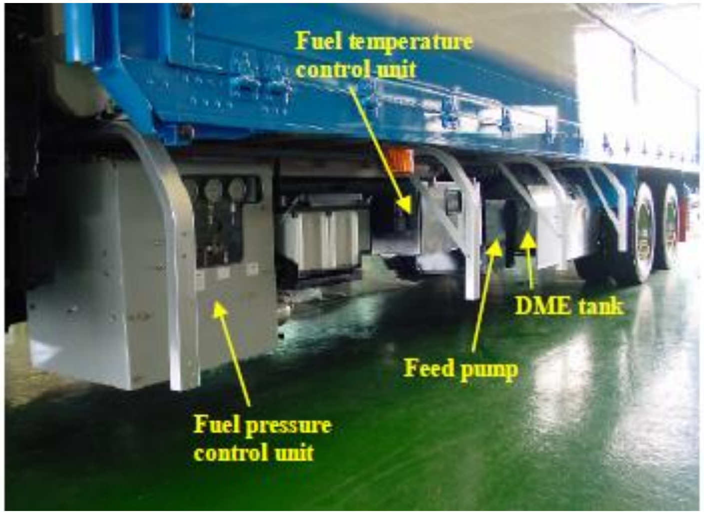
Source: Bioethanol for Sustainable Transport (BEST) Final Report Feb 2010
ETN/ETSAP Technology Brief T06 June 2010

Bio Dimethyl Ether (DME) can be burnt in an adapted Diesel engine

Bio Dimethyl Ether (DME)

- **Description:** engine and fuel system adapted to burn bio-DME, which has a low boiling point and therefore must be stored in pressurised fuel tank and allowed to evaporate as it is injected into the engine. FIE and calibration likely to require adaptation. Trialled by Scandinavian manufacturers using DME made from forestry / pulp industry by-products
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 8 – 90 bus fleet running in Shanghai, although not neccesarily bio-DME
- **Potential Fuel Savings and CO_2 Benefit:** 2% reduction in tailpipe CO_2. WTW CO_{2eq} 104% less than diesel bus WTW CO_2 emissions. DME can be made from natural gas but the WTW CO_{2eq} is no better than diesel
- **Technology Price:** Technology price expected to be ~50% of on-cost of gas (including liquid fuel storage but with some liquefaction required, modified FIE). Fuel cost expected ~1.5x diesel based on Japan experience
- **Maintenance Cost:** Not expected higher than diesel

	SD	DD
TRL	8	8
Development to TRL 9	M	M
TTW CO_2 Benefit (%)	2	2
WTT CO_2 Benefit (%)	104	104
Technology Price (£)	22500	22500
Maintenance Cost (£)	0	0



Picture Source: see ref ...

Source: Ricardo Analysis
Development of a DME Fuelled Heavy Duty Truck – NTSEL(Japan)/Nissan Diesel Motor Co 2005

Compressed Natural Gas (CNG) in stoichiometric SI engine

CNG in stoich SI Engine

- **Description:** an OEM designed gas fuelled spark ignited (Otto) engine installed from new or re-engined into an existing bus, burning natural gas from the grid. The engine is stoichiometric (no excess air) with three way catalyst, fuel consumption approx. 30% poorer than diesel. Engine out CO_2 is consequently ~1% poorer than diesel. The same technology can be used to burn CBG
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 9, Engine technology for buses is mature. CNG and biomethane fuelling infrastructure is currently niche in the UK
- **CO_2 Benefit:** Engine out CO_2 is degraded due to the mass penalty of the fuel tanks (typically>500kg for 300mi range with a Type 2 tank) to give a slight increase in TTW CO_2 emissions. A range is shown for WTW CO_2 to show the effect of different gas supply pathways (as detailed in slide 98)
- **Technology Price:** Costs are based on public domain information from US CNG bus study by MJ Bradley & Associates, and omit the effect of refuelling infrastructure costs.
- **Maintenance Cost:** some periodic leak check activities
- **Retrofit potential:** Retrofit involves replacement of the bus diesel engine with spark ignited engine . Space must be found for the gas tanks which have a significant volume and mass impact on vehicle packaging and vehicle dynamics. Packaging systems is challenging for a double deck as tanks cannot be stored on the roof.

	SD	DD
TRL	9	7
Development to TRL 9	-	H
TTW CO_2 Benefit (%)	-4	-4
WTW CO_2 Benefit (%)	+5 to -16	+5 to -16
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Picture Source: .MAN..

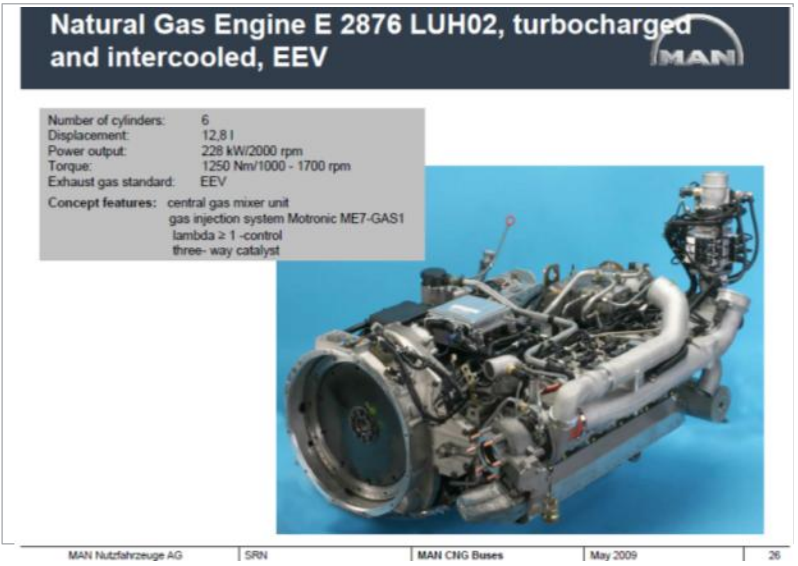
Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Compressed Natural Gas (CNG) in lean burn SI engine

CNG in lean SI Engine

- **Description:** an OEM designed gas fuelled spark ignited (Otto) engine installed from new or re-engined into an existing bus, burning natural gas from the grid. The engine is lean burn (with excess air) or mixed mode lean/stoich. Fuel consumption approx. 25% poorer than diesel. Engine out CO_2 is consequently ~4% better than diesel. The same technology can be used to burn CBG
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 9, Engine technology for buses is mature. CNG and biomethane fuelling infrastructure is currently niche in the UK
- **CO_2 Benefit:** The slightly better engine out CO_2 is negated by the mass penalty of the fuel tanks (typically>500kg for 300mi range with a Type 2 tank) resulting in a broadly neutral TTW figure. A range is shown for WTW CO_2 to show the effect of different gas supply pathways (as detailed in slide 98)
- **Technology Price:** Costs are based on public domain information from US CNG bus study by MJ Bradley & Associates, and omit the effect of refuelling infrastructure costs
- **Maintenance Cost:** some periodic leak check activities
- **Retrofit potential:** Retrofit involves replacement of the bus diesel engine with spark ignited engine . Space must be found for the gas tanks which have a significant volume and mass impact on vehicle packaging and vehicle dynamics. Packaging CNG systems is challenging for a double deck as tanks cannot be stored on the roof.

	SD	DD
TRL	9	7
Development to TRL 9	-	H
TTW CO_2 Benefit (%)	1	1
WTW CO_2 Benefit (%)	+10 to -11	+10 to -11
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500



Natural Gas Engine E 2876 LUH02, turbocharged and intercooled, EEV

Number of cylinders: 6
Displacement: 12,8 l
Power output: 228 kW/2000 rpm
Torque: 1250 Nm/1000 - 1700 rpm
Exhaust gas standard: EEV

Concept features: central gas mixer unit
gas injection system Motronic ME7-GAS1
lambda ≥ 1 -control
three- way catalyst

MAN Nutzfahrzeuge AG | SRN | MAN CNG Buses | May 2009 | 26

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Liquified Natural Gas (LNG) in lean diesel pilot engine

LNG in lean diesel pilot Engine

- **Description:** Westport gas fuelled diesel pilot ignited (Diesel cycle) engine Gas and a small amount of diesel fuel is injected direct into the cylinder. The engine is lean burn (with excess air). Fuel handling on vehicle is LNG and therefore does not lend itself to direct grid supply. Fuel consumption is estimated approx. 12% poorer than diesel and therefore engine out CO_2 is expected ~18% better than diesel. The same technology can be used to burn LBG and has a natural fit with the Gasrec LBG supply model
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Westport currently only manufacture 15l/12l engines which are overpowered for bus applications. Would require new small engine adaptation
- **CO_2 Benefit:** The better engine out CO_2 is slightly offset by the mass penalty of the fuel tanks (typically>350kg for 300mi range) resulting in a beneficial TTW figure. A range is shown for WTW CO_2 to show the effect of different gas supply pathways (as detailed in slide 98)
- **Technology Price:** No specific costs are available for the Westport system and it is not available in bus sized models therefore the same cost assumptions for the previous SI engines are used
- **Maintenance Cost:** some periodic leak check activities
- **Retrofit potential:** Retrofit involves replacement of the bus diesel engine with gas engine . Space must be found for the gas tanks which have a significant volume and mass impact on vehicle packaging and vehicle dynamics. Packaging CNG systems is challenging for a double deck as tanks cannot be stored on the roof.

	SD	DD
TRL	7	5
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	15	15
WTW CO_2 Benefit (%)	+23 to +4	+23 to +4
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Picture Source: .Westport

Source: Ricardo Analysis, Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Anaerobic digestion (AD) biomethane in stoichiometric SI engine

AD biomethane in stoich SI Engine

- **Description:** as for stoich CNG SI engine, instead burning biomethane generated by AD injected into the grid. Since the biomethane is upgraded to grid quality, engine technology and TTW performance is identical to the CNG stoich case: fuel consumption approx. 30% poorer than diesel. Engine out CO_2 is consequently ~1% poorer than diesel. The WTW benefit comes from the WTT performance of the biomethane
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 8, Engine technology is mature. biomethane AD & fuelling infrastructure is currently niche in the UK but growing. Accounting system to ensure attribution of grid injected biomethane to transport fuel needs to be in place
- **CO_2 Benefit:** Engine out CO_2 is degraded due to the mass penalty of the fuel tanks (typically>500kg for 300mi range with a Type 2 tank) to give a slight increase in TTW CO_2 emissions. However this is insignificant when the high WTW CO_2 benefit is included. See AD biomethane slides for description of fuel pathway WTT CO_2
- **Technology Price:** Costs assumed same as CNG case.
- **Maintenance Cost:** some periodic leak check activities
- **Retrofit potential:** Same as CNG

*For clarity: CO_2 benefit >100% implies a negative WTW CO2

	SD	DD
TRL	8	6
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	-4	-4
WTW CO_2 Benefit (%)	146*	146
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Picture Source: .biomethane Nord/MAN..

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

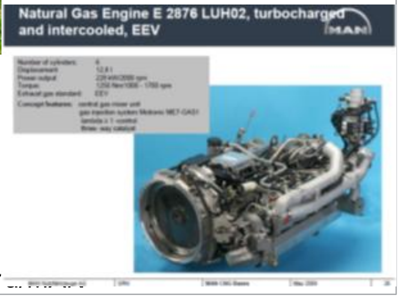
Anaerobic digestion (AD) biomethane in lean burn SI engine

AD biomethane in lean SI Engine

- **Description:** as for lean CNG SI engine, instead burning biomethane generated by AD injected into the grid. Since the biomethane is upgraded to grid quality, engine technology and TTW performance is identical to the CNG lean case: fuel consumption approx. 25% poorer than diesel. Engine out CO_2 is consequently ~4% better than diesel. The strong benefit comes from the WTT performance of the biomethane
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 8, Engine technology is mature. biomethane AD & fuelling infrastructure is currently niche in the UK but growing. Accounting system to ensure attribution of grid injected biomethane to transport fuel needs to be in place
- **CO_2 Benefit:** The slightly better engine out CO_2 is negated by the mass penalty of the fuel tanks (typically>500kg for 300mi range with a Type 2 tank) resulting in a broadly neutral TTW figure. However this is insignificant when the high WTW CO_2 benefit is included. See AD biomethane slides for description of fuel pathway WTT CO_2
- **Technology Price:** Costs assumed same as CNG case.
- **Maintenance Cost:** some periodc leak check activities
- **Retrofit potential:** Same as CNG

*Paradoxically, a more efficient technology burning a negative carbon fuel results in lower WTW benefit relative to diesel. However when the negative carbon fuel is supply-side limited , the highest efficiency technology should be used in order to maximise uptake across as many vehicles as possible

	SD	DD
TRL	8	6
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	1	1
WTW CO_2 Benefit (%)	143*	143
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500



Natural Gas Engine E 2876 LUH02, turbocharged and intercooled, EEV

Picture Source: .biomethane Nor

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Anaerobic digestion (AD) biomethane in lean diesel pilot engine

AD biomethane in lean diesel pilot engine

- **Description:** As per LNG Westport case, instead burning liquefied biomethane therefore does not lend itself to grid injected AD biomethane supply. Fuel consumption is only approx. 12% poorer than diesel and therefore engine out CO_2 is ~17% better than diesel. The same technology can be used to burn LBG but has a natural fit with the Gasrec LBG supply model rather than the AD CBG route
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Westport currently only manufacture 15l/12l engines which are overpowered for bus applications. Would require new small engine adaptation. biomethane AD & fuelling infrastructure is currently niche in the UK but growing, but this engine technology requires fuel delivered as LBG and so an additional stage is required
  - **CO_2 Benefit:** The better engine out CO_2 is slightly offset by the mass penalty of the fuel tanks (typically>350kg for 300mi range) resulting in a beneficial TTW figure. However this is insignificant when the high WTW CO2 benefit is included. See AD biomethane slides for description of fuel pathway WTT CO_2
- **Technology Price:** Costs assumed same as CNG case.
- **Maintenance Cost: :** some periodc leak check activities
- **Retrofit potential:** Same as CNG

	SD	DD
TRL	6	4
Development to TRL 9	H	H
TTW CO_2 Benefit (%)	15	15
WTW CO_2 Benefit (%)	142	142
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Picture Source: .biomethane Nord/Westport

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Landfill liquefied biomethane (LBM) in stoichiometric SI engine

LBM in stoich SI engine

- **Description:** as for stoich CNG SI engine, instead burning biomethane generated from landfill and delivered as LBM. It is assumed the biomethane is upgraded to grid quality, engine technology and TTW performance is identical to the CNG stoich case: fuel consumption approx. 30% poorer than diesel. Engine out CO_2 is consequently ~1% poorer than diesel. The benefit comes from the WTT performance of the biomethane
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 8, Engine technology is mature. Landfill biomethane & LBG fuelling infrastructure is currently niche in the UK but growing. Direct delivery of biofuel to user removes the need for any accounting system
- **CO_2 Benefit:** Engine out CO_2 is degraded due to the mass penalty of the fuel tanks (typically>500kg for 300mi range with a Type 2 tank) to give a slight increase in TTW CO_2 emissions. However this is insignificant when the high WTW CO_2 benefit is included. See landfill liquified biomethane slides for description of fuel pathway WTT CO_2
- **Technology Price:** Costs assumed same as CNG case.
- **Maintenance Cost:** some periodic leak check activities
- **Retrofit potential:** Same as CNG

	SD	DD
TRL	8	6
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	-4	-4
WTW CO_2 Benefit (%)	70	70
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Picture Source: .Gasrec/MAN..

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Landfill liquefied biomethane (LBM) in lean burn SI engine

LBM in lean SI engine

- **Description:** as for lean CNG SI engine, instead burning biomethane generated from landfill and delivered as LBM. It is assumed the biomethane is upgraded to grid quality, engine technology and TTW performance is identical to the CNG lean case: fuel consumption approx. 25% poorer than diesel. Engine out CO_2 is consequently ~4% better than diesel. The strong WTW benefit comes from the WTT performance of the biomethane
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 8, Engine technology is mature. Landfill biomethane & LBG fuelling infrastructure is currently niche in the UK but growing. Direct delivery of biofuel to user removes the need for any accounting system
- **CO_2 Benefit:** The slightly better engine out CO_2 is negated by the mass penalty of the fuel tanks ((typically>500kg for 300mi range with a Type 2 tank) resulting in a broadly neutral TTW figure. However this is insignificant when the high WTW CO_2 benefit is included. See landfill liquified biomethane slides for description of fuel pathway WTT CO_2
- **Technology Price:** Costs assumed same as CNG case.
- **Maintenance Cost:** some periodic leak check activities
- **Retrofit potential:** Same as CNG

	SD	DD
TRL	8	6
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	1	1
WTW CO_2 Benefit (%)	71	71
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Natural Gas Engine E 2876 LUH02, turbocharged and intercooled, EEV

Picture Source: .biomethane Nor

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Landfill liquefied biomethane (LBM) in lean diesel pilot engine

LBM in lean diesel pilot engine

- **Description:** As per LNG Westport case, instead burning liquefied biomethane generated from landfill and delivered by tanker. Fuel consumption is only approx. 12% poorer than diesel and therefore engine out CO_2 is ~17% better than diesel
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: Westport currently only manufacture 15l/12l engines which are overpowered for bus applications. Would require new small engine adaptation. biomethane AD & fuelling infrastructure is currently niche in the UK but growing
  - **CO_2 Benefit:** The better engine out CO_2 is slightly offset by the mass penalty of the fuel tanks (t typically>350kg for 300mi range) resulting in a beneficial TTW figure. However this is insignificant when the high WTW CO_2 benefit is included. See landfill liquified biomethane slides for description of fuel pathway WTT CO_2
- **Technology Price:** Costs assumed same as CNG case.
- **Maintenance Cost: :** some periodic leak check activities
- **Retrofit potential:** Same as CNG

	SD	DD
TRL	7	5
Development to TRL 9	M	H
TTW CO_2 Benefit (%)	15	15
WTW CO_2 Benefit (%)	78	78
Technology Price (£)	45,000	45,000
Maintenance Cost (£)	500	500

Picture Source: .biomethane Nord/Westport

Source: Clean Diesel vs CNG City Buses, MJB&A Feb 2012...

Hydrogen Internal Combustion Engine

Hydrogen ICE

- **Description:** Hydrogen has a high mass calorific value and low ignition energy, but low density and hence volumetric calorific value. It can be burned safely in a modified (lowered compression ratio, modified ignition system) SI engine which resembles a stoich CNG engine
- **Technology Readiness Level (TRL):**
  - Current Technology Maturity: 8, HYFLEET:CUTE project ran fleets of H2 ICE (and FC) buses over 4 years and millions of miles, with 89% availability
  - Like natural gas fuel buses, packaging H_2 systems is challenging for a double deck as tanks cannot be stored on the roof.
- **Potential Fuel Savings and CO_2 Benefit:** 100% tailpipe TTW CO_2 benefit (zero emissions). Renewable best and worst case WTW ranges from 66-92% benefit depending on renewable hydrogen pathway
- **Technology Price:** assumed same as CNG stoich equivalent, price does not include hydrogen refuelling infrastructure costs
- **Maintenance Cost:** Specialist maintenance facilities and procedures for dealing with H_2, ICE relatively straightforward

Source: ...

	SD	DD
TRL	8	6
Development to TRL9	M	H
TTW CO_2 Benefit (%)	100	100
WTT CO_2 Benefit (%)	66-92	66-92
Technology Price (£)	45000	45000
Maintenance Cost (£)	5000	5000

Picture Source: Global Hydrogen Bus Platform/HYFLEET:CUTE...

Technologies were selected for inclusion in this study where they are expected to give >2 % CO2 reduction compared to the baseline

Technologies

Vehicle

- Lightweighting

Powertrain

- Parasitic loss reduction: smart clutched compressor, smart alternator
- Waste heat recovery/thermal management: rankine cycle using engine coolant and exhaust
- Driveline: IVT
- Hybridisation: stop start, mild hybrid, series and parallel electric and hydraulic hybrids

Fuel

- Fossil fuels: Compressed natural gas (CNG)
- Biofuels: Compressed biomethane (CBG), HVO, BTL
- Other fuels: Hydrogen (Internal combustion engines and fuel cell), electricity

Contents

Assessment of the return on investment for each technology is calculated based on a set of assumptions about bus operations

- **Annual mileage** is based on the recommendation of the LowCVP Bus Working Group for buses covering an urban duty cycle
- **Fuel consumption** is based on road test fuel consumption data from public domain sources combined with recommendations from the LowCVP Bus Working Group
- **Fuel price** - a constant fuel price is assumed, based on expected fleet fuel prices in 2012, excluding VAT but including fuel duty
- **Technology price** – based on the additional bill of materials cost of a complete system with a markup of 100% to provide an estimate for vehicle price increase **(not including, for example, additional costs for operators such as infrastructure or capital financing)**
- **Maintenance costs** – An estimate for the change in running costs compared to a baseline bus is included in calculations of return on investment where the technology has a direct effect on Maintenance costs
- **Effect of capital and fuel subsidies** on payback time is illustrated by calculating payback time both with and without subsidies
  - It is assumed that a maximum 80% subsidy is obtained for technologies that give >30% WTW GHG benefit and biomethane buses
- No allowance is made in these calculations for the cost of borrowing or inflation

	Single Deck Bus	Double Deck Bus
Annual mileage (miles)	40,000	40,000
Fuel consumption (mpg)	8	6

Source: Ricardo analysis, LowCVP bus working group, Autobus, Route 1, Bus and Coach Buyer

Fuel prices assumed in this study are based on 2012 prices

- Fuel price paid by operators is a combination of base fuel price, fuel duty and BSOG
  - Base fuel prices are based on public domain information
  - Duty and BSOG values are as applicable on 1 September 2012
- An additional fuel subsidy is available for low carbon buses
  - 6p per km is available for buses that give a 30% reduction in GHG emissions, equivalent to £3871 per year for the annual mileage assumed in this study
- Return on investment will be assessed both with and without subsidy payments

	Base price	Fuel duty	BSOG	Price with BSOG	Price without BSOG
Diesel fuel price (pence per litre)	50	57.95	34.57	73.4	107.95
Bioethanol (pence per litre)	50	57.95	34.57	73.4	107.95
CNG fuel price (pence per kg)	60.3	24.70	18.88	66.12	85.0
CBG fuel price (pence per kg)	60.3	24.70	18.88	66.12	85.0
Electricity price (pence per kWh)	8.5	NA	NA	NA	NA
Hydrogen (pence per kg)	1000 - green 2000 - industrial	NA	NA	NA	NA

Source: DfT (https://www.gov.uk/fuel-duty#rates-of-fuel-duty), Go Ahead annual reports

Costs and benefits were identified for technologies expected to give > 2% GHG reduction for UK urban buses

Technology description	Technology price (£)*		Maintenance cost (£ per year)		TTW CO_2 benefit (% change)		WTW CO_2 benefit (% change)	
Single/Double Deck	SD	DD	SD	DD	SD	DD	SD	DD
Lightweighting step 1	6000	10000	-	-	3	3	3	3
Lightweighting step 2	18000	25000	-	-	7	8	7	8
Smart alternator	600	600	-	-	5	5	5	5
Smart compressor	500	500	-	-	6	6	6	6
Rankine cycle heat recovery (exhaust)	9000	12000	-	-	3	4	3	4
Rankine cycle heat recovery (coolant)	9000	12000	-	-	3	3	3	3
IVT	15000	15000	-	-	15	15	15	15
Stop/start system	1400	1400	-500	-500	9	9	9	9
Mild hybrid system	6000	6400	60	60	13	13	13	13
Full hybrid – parallel (incl battery replacement)	90000	105000	-3273	-3940	35	35	35	35
Full hybrid – series (incl battery replacement)	75000	90000	-3940	-4607	40	40	40	40
Full hybrid – parallel hydraulic	37500	37500	60	60	20	20	20	20
Full hybrid – series hydraulic	37500	37500	60	60	35	35	35	35
Flywheel energy storage	15000	15000	60	60	17	17	17	17
Pneumatic booster system	600	600	-	-	3	3	3	3
Battery Electric Vehicle (incl battery replace.)	97500	105000	-4940	-6607	100	100	30	30
Trolley bus	300000	500000	-	-	100	100	24	24

*Trolley bus price does not include infrastructure cost
Price not including subsidies ^ Positive figure indicates better/less than baseline diesel, negative worse/more

WTW benefits of alternative fuels were reviewed, including consideration of UK CNG pathways

Technology description	Technology price (£)*		Maintenance cost (£ per year)		TTW CO_2 benefit (% change)^		WTW CO_2 benefit (% change)^	
Single/Double Deck	SD	DD	SD	DD	SD	DD	SD	DD
CNG in stoich (range of UK pathways)	45000	45000	-500	-500	-4	-4	+5 to -16	+5 to -16
CNG in Lean Burn (range of UK pathways)	45000	45000	-500	-500	1	1	+10 to -11	+10 to -11
LNG in Diesel Pilot (range of UK pathways)	45000	45000	-500	-500	15	15	+23 to +4	+23 to +4
AD biomethane in Stoich	9000	9000	-500	-500	-4	-4	146	146
AD biomethane in Lean Burn	9000	9000	-500	-500	1	1	143	143
AD biomethane in Diesel Pilot	9000	9000	-500	-500	15	15	142	142
Landfill Liquefied biomethane in Stoich	9000	9000	-500	-500	-4	-4	70	70
Landfill Liquefied biomethane in Lean Burn	9000	9000	-500	-500	1	1	71	71
Landfill Liquefied biomethane in Diesel Pilot	9000	9000	-500	-500	15	15	78	78
Bioethanol E95 in CI engine (5% ignition enhancer)	21000	32000	-	-	2	2	68	68
Hydrogen FC (Industrially sourced H_2)	600000	700000	-10000	-10000	100	100	17	17
Hydrogen FC (renewable H_2)	600000	700000	-10000	-10000	100	100	75 to 94	75 to 94
Hydrogen ICE (Industrially sourced H_2)	45000	45000	-	-	100	100	-15	-15
Hydrogen ICE (renewable H_2)	45000	45000	-	-	100	100	66 to 92	66 to 92
Bio Dimethyl Ether (DME)	22500	22500	-	-	6	6	104	104
BTL	-	-	-	-	0	0	92	92
HVO	-	-	-	-	0	0	60	60

* Price not including subsidies ^ Positive figure indicates better/less than baseline diesel, negative worse/more

Payback time is calculated from technology costs, fuel savings and maintenance costs

- **It should be noted that Technology price is based only on the additional bill of materials cost of a complete system with a markup of 100% to provide an estimate for vehicle price increase**
  - **Additional costs for operators such as infrastructure or capital financing are not included which may increase operators costs and therefore payback time**

Payback (P) = - technology cost (T) / (fuel saving (F) + maintenance cost (M))

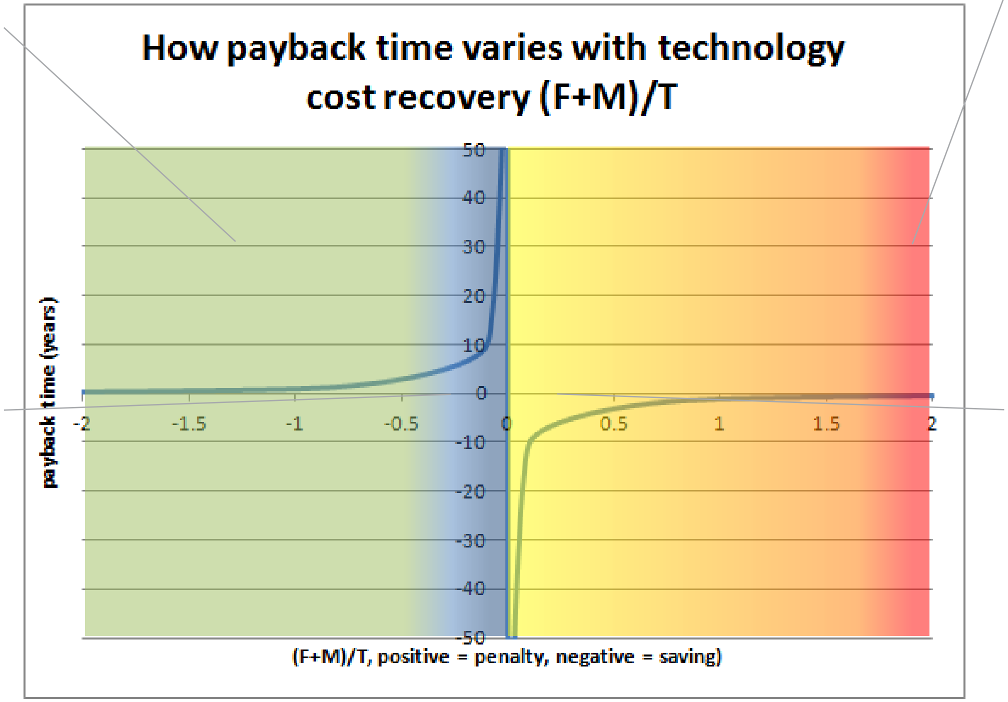
- If annual maintenance costs are greater than diesel, then M is positive
- If fuel cost is less than baseline diesel (either by reduced diesel consumption, or substitution with a fuel of lower annual cost), F is negative
- Where annual fuel costs are greater than diesel (F is positive) – then payback is negative i.e. the technology will not break even, regardless of capital cost (unless there is a large saving in maintenance costs)
- Looking at the table on slide 122, it is clear that different technologies respond in different ways to the presence/absence of capital and fuel subsidies. This is explainable as follows:
  - The value of fuel saving reduces with the inclusion of BSOG, as fuel is less expensive for the operator – i.e. when BSOG is included, payback times increase
  - If the technology has subsidies additional to those for baseline diesel technology – i.e. 6p per km for LCEB, then payback time increases without this additional subsidy

Payback time is a complex relationship between annual fuel and maintenance costs and technology on-cost

- In this plot, the x-axis is annual fuel + maintenance cost change from baseline, divided by technology cost, so a value of -1 means annual fuel + maintenance saving (negative change) exactly balances technology on-cost

Green zone: large F+M saving more than compensates for technology cost resulting in short (positive) payback time

Blue zone: F+M saving is small and compensates for technology cost only over a long (positive) payback time. Where F+M saving is very small relative to technology cost, payback time rapidly increases asymptotically



Saving

Penalty

Red zone: large F+M penalty results in numerically small negative payback, but means in reality a strong disincentive to use the technology unless other compelling reasons exist

Yellow zone: F+M penalty is small resulting in numerically large negative payback – there may be other compelling reasons to adopt the technology (air quality, noise) so this small F+M penalty may be bearable

Technologies can flip from -ve to +ve payback (and in some cases large –ve to large +ve) by the application of a running cost subsidy like LCEB p/km, which changes a fuel cost penalty to a fuel cost saving). However without that running cost subsidy, a non fuel-cost saving technology cannot be changed from negative to positive payback simply by reducing the technology cost via subsidy (unless operators are positively paid to use the technology)

Time to receive a return on investment has been calculated based on the study assumptions for annual mileage and fuel prices

Current regime

Technology	Payback time (years)							
	With BSOG No capital subsidy		No BSOG No capital subsidy		With BSOG with capital subsidy		No BSOG with capital subsidy	
Single/Double Deck	SD	DD	SD	DD	SD	DD	SD	DD
Lightweighting step 1	12.2	13.9	8.3	9.4	12.2	13.9	8.3	9.4
Lightweighting step 2	15.7	13.9	10.7	9.4	15.7	13.9	10.7	9.4
Smart alternator	0.6	0.4	0.4	0.3	0.6	0.4	0.4	0.3
Smart compressor	0.6	0.4	0.4	0.3	0.6	0.4	0.4	0.3
Rankine cycle heat recovery (exhaust)	18.3	12.5	12.4	8.5	18.3	12.5	12.4	8.5
Rankine cycle heat recovery (coolant)	18.3	16.7	12.4	11.3	18.3	16.7	12.4	11.3
IVT	6.1	4.2	4.1	2.8	6.1	4.2	4.1	2.8
Stop/start system	1.4	0.8	0.8	0.5	1.4	0.8	0.8	0.5
Mild hybrid system	2.7	2.0	1.9	1.4	2.7	2.0	1.9	2.7
Full hybrid – parallel (incl battery replacement)	14.2	12.6	17.4	12.5	2.8	2.5	3.5	2.5
Full hybrid – series (incl battery replacement)	11.6	10.1	13.1	9.4	2.3	2.0	2.6	1.9

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh

The prevailing subsidy regime has a significant and complex effect on payback times

Technology	**Payback time (years)**							
	With BSOG No capital subsidy		**No BSOG No capital subsidy**		**With BSOG with capital subsidy**		**No BSOG with capital subsidy**	
	SD	DD	SD	DD	SD	DD	SD	DD
Full hybrid – parallel hydraulic	11.2	7.7	7.7	5.3	11.2	7.7	7.7	5.3
Full hybrid – series hydraulic	3.9	3.0	4.4	3.0	0.8	0.6	0.9	0.6
Flywheel energy storage	5.3	3.6	3.6	2.5	5.3	3.6	3.6	2.5
Pneumatic booster system	1.2	0.8	0.8	0.6	1.2	0.8	0.8	0.6
Battery Electric Vehicle	62.9	36.3	10.5	7.4	12.6	7.3	2.1	1.5
Trolley bus	34.4	39.2	18.2	20.8	34.4	39.2	18.2	20.8
CNG Stoich	-	-	16.8	10.9	-	-	16.8	10.9
CNG Lean	101.4	51.0	11.9	7.8	101.4	51.0	11.9	7.8
LNG in diesel pilot	22.2	14.1	7.7	5.1	22.2	14.1	7.7	5.1
Biomethane in Stoich	13.0	13.3	16.8	10.9	2.6	2.7	3.4	2.2
Biomethane in Lean Burn	10.4	9.5	11.9	7.8	2.1	1.9	2.4	1.6
Biomethane in Diesel Pilot	7.6	6.4	7.7	5.1	1.5	1.3	1.5	1.0
Bioethanol E95 in CI engine	-	-	-	-	-	-	-	-
Hydrogen ICE	-	-	-	-				
Hydrogen fuel cell	-	-	-	-				

High current fuel prices mean that a break even point is not achieved for hydrogen and Bioethanol powered vehicles

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh

Payback time decreases without BSOG, or where a capital subsidy is applicable

Technology	**Payback time (years)**							
	With BSOG No capital subsidy		**No BSOG No capital subsidy**		**With BSOG with capital subsidy**		**No BSOG with capital subsidy**	
Single/Double Deck	SD	DD	SD	DD	SD	DD	SD	DD
Lightweighting step 1	12.2	13.9	8.3	9.4	12.2	13.9	8.3	9.4
Lightweighting step 2	15.7	13.9	10.7	9.4			10.7	9.4
Smart alternator	0.6	0.4	0.4	0.3			0.4	0.3
Smart compressor	0.6	0.4	0.4	0.3	0.6	0.4	0.4	0.3
Rankine cycle heat recovery (exhaust)	18.3	12.5	12.4	8.5	18.3	12.5	12.4	8.5
Rankine cycle heat recovery (coolant)	18.3	16.7	12.4	11.3	18.3	16.7	12.4	11.3
IVT				2.8	6.1	4.2	4.1	2.8
Stop/start system				0.5	1.4	0.8	0.8	0.5
Mild hybrid system	2.7	2.0	1.9	1.4	2.7	2.0	1.9	2.7
Full hybrid – parallel (incl battery replacement)	14.2	12.6	17.4	12.5	2.8	2.5	3.5	2.5
Full hybrid – series (incl battery replacement)	11.6	10.1	13.1	9.4		2.0	2.6	1.9

Payback time reduces without BSOG due to increased fuel price

Payback time increases without BSOG for technologies eligible 6p/km subsidy

Payback time reduces for technologies eligible for capital subsidy where they are available

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh

CNG stoich and lean technologies only payback when there is no BSOG due to higher fuel consumption and technology price

Technology	Payback time (years)							
	With BSOG No capital subsidy		No BSOG No capital subsidy		With BSOG with capital subsidy		No BSOG with capital subsidy	
	SD	DD	SD	DD	SD	DD	SD	DD
Full hybrid – parallel hydraulic	11.2	7.7	7.7	5.3	11.2	7.7	7.7	5.3
Full hybrid – series hydraulic	3.9	3.0	4.4	3.0	0.8	0.6	0.9	0.6
Flywheel energy storage	5.3	3.6	3.6	2.5	[illegible]	3.6	3.6	2.5
Pneumatic booster system	1.2	0.8	0.8	[illegible]	[illegible]	0.8	0.8	0.6
Battery Electric Vehicle	62.9	36.3	10.5	[illegible]	[illegible]	7.3	2.1	1.5
Trolley bus	34.4	39.2	18.2	20.8	34.4	39.2	18.2	20.8
CNG Stoich	-	-	16.8	10.9	-	-	16.8	10.9
CNG Lean	101.4	51.0	11.9	7.8	101.4	51.0	11.9	7.8
LNG in diesel pilot	22.2	[illegible]	7.7	5.1	22.2	14.1	7.7	5.1
Biomethane in Stoich	13.0	[illegible]	[illegible]	[illegible]	2.6	2.7	3.4	2.2
Biomethane in Lean Burn	10.4	[illegible]	[illegible]	[illegible]	2.1	1.9	2.4	1.6
Biomethane in Diesel Pilot	7.6	[illegible]	[illegible]	[illegible]	1.5	1.3	1.5	1.0
Bioethanol E95 in CI engine	-	-	-	-	-	-	-	-
Hydrogen ICE	-	-	-	-	-	-	-	-
Hydrogen fuel cell	-	-	-	-	-	-	-	-

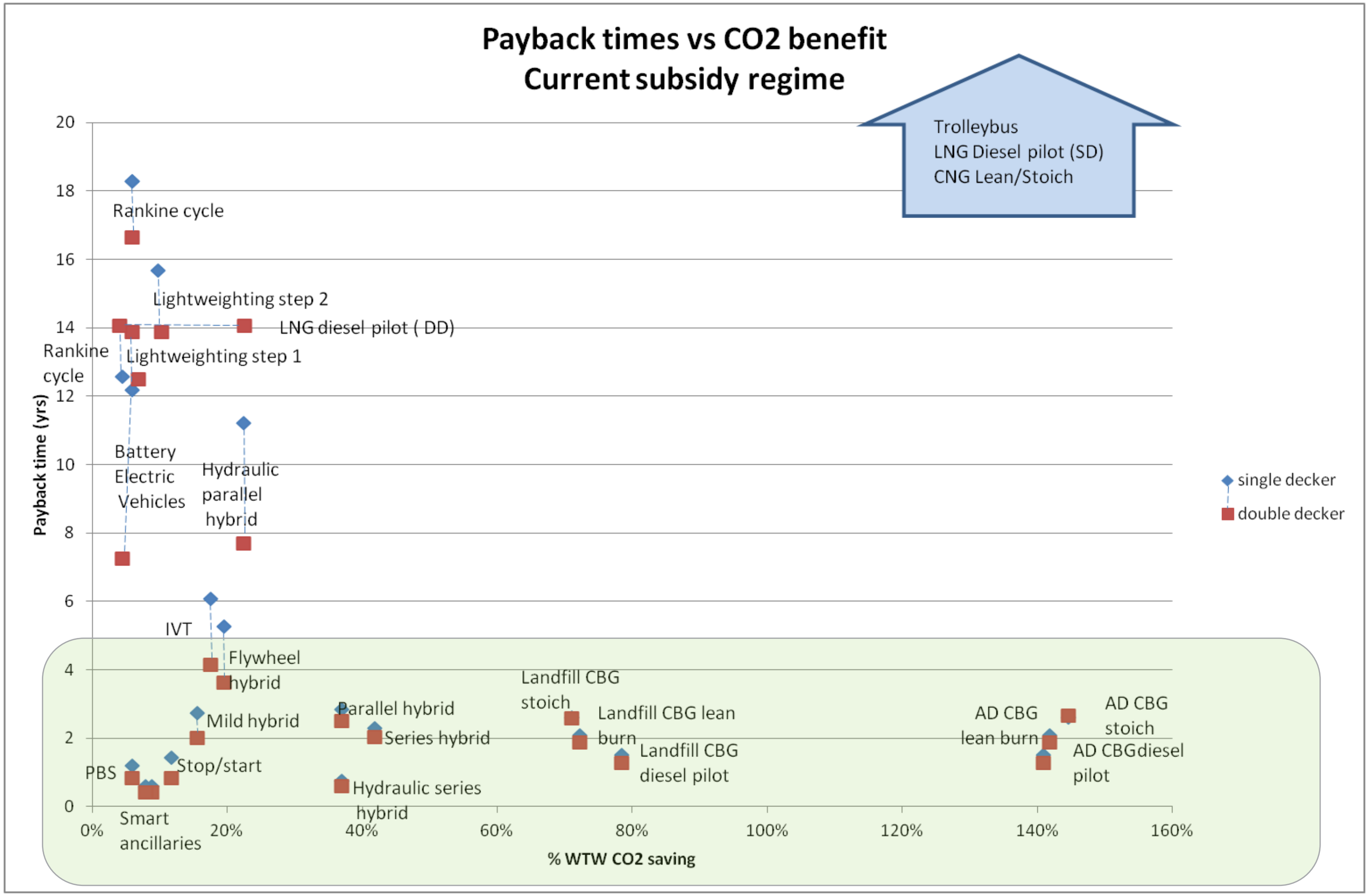
Payback time reduces for technologies eligible for capital subsidy

A combination of high technology price, maintenance cost and small fuel cost saving mean that CNG stoich buses only pay back without BSOG

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh

Payback times were assessed, based on assumptions about bus operations and fuel prices, under the current subsidy regime..

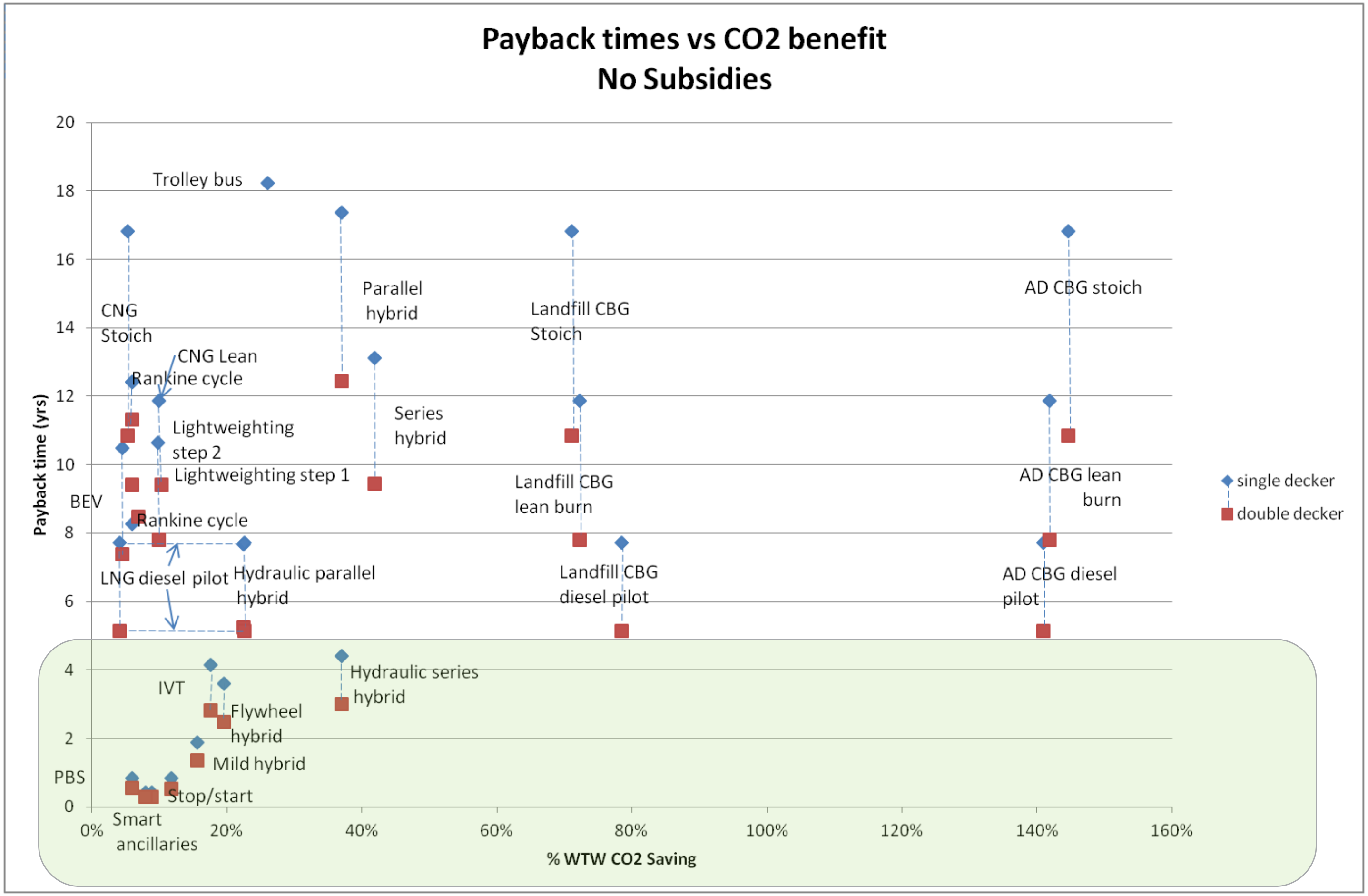
- Highlighted area shows payback time < 5 yrs
- The following technologies lie in this zone, given the study assumptions:
  - Biomethane powered engines, stop start, PBS, smart ancillaries, mild hybrid, flywheel hybrid, parallel and series battery hybrids, series hydraulic hybrid, IVT
- BSOG increases payback times due to lower effective fuel cost



Assumptions: 40000 miles pa both SD and DD; fuel consumption 8mpg SD, 6mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh.

..and with no subsidies – UK subsidies were found to have a significant and complex effect on commercial viability

- With no subsidies, full battery hybrid and gas powered technologies have payback times of greater than 5 years
  - Series hydraulic hybrid, mild hybrid and flywheel hybrid technologies still have payback times less than 5 years
- Measures to reduce ancillary power use, stop start, IVT and pneumatic booster systems also payback in less than 5 years
- Note that reducing subsidies also increases operating costs for a standard diesel bus



Assumptions: 40000 miles pa both SD and DD; fuel consumption 8mpg SD, 6mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12, electricity 8.5ppkWh.

Contents

Technologies were excluded where they were considered unsuitable for bus use or were expected to give < 2% CO_2 benefit (1/4)

Technology Description	Comments
Aerodynamic body / fairings	Low speed duty cycle and limited potential with bus body shape
Low rolling resistance tyres/tyre pressure adjustment	Bus tyres generally leased from suppliers who are responsible for full service provision. Low RR tyres are on offer but their application to buses is limited by conflict with the need for cushioned/kerb-strike resistant sidewalls. See also slides 136-139
Predictive cruise control	Many buses already have topographic shift schedule optimisation (e.g.ZF Topodyn) and so the elements of Predictive CC which would contribute to major fuel savings can be considered a baseline technology
Vehicle platooning	Not relevant for bus application. May be relevant to coach application
Driver training	See slides 136-139
Gas exchange/pumping work optimisation	Air/EGR system development is always under development by OEM to ensure BSFC-neutral compliance with next emissions stage. Limited BSFC benefit per se and difficult to influence
Combustion system	Combustion system developments (higher pressure injection, combustion chamber) are always under development by OEM to ensure BSFC-neutral compliance with next emissions stage. Limited BSFC benefit per se and difficult to influence

Technologies were excluded where they were considered unsuitable for bus use or were expected to give < 2% CO_2 benefit (2/4)

Technology Description	Comments
Engine downsizing	Engines considered to be ‘rightsized’ currently, medium/heavy duty engines already running on relatively flat BSFC-load curve (unlike pass car). Engine downspeeding is a relevant trend which OEMs will apply in any case
Engine friction work optimisation/design for low friction	Friction work dominates at high engine speed, little benefit on bus cycle - OEM would be expected to implement for new engines, limited opportunity to influence
Fuel additives	See detailed discussion on slide 133-135
Variable flow water / lubricant pump	Benefits only significant for high engine speed duty cycles
Turbo compounding (electrical/mechanical)	Benefits only significant for high engine speed/high power duty cycles
Stirling engine/thermoelectric generator as exhaust heat recovery	Extremely low power density

Technologies were excluded where they were considered unsuitable for bus use or were expected to give < 2% CO_2 benefit (3/4)

Technology Description	Comments
Heat to cool system (powers aircon from bus engine heat)	Not relevant since buses don’t typically have aircon except in drivers cab. If this situation is likely to change (i.e. saloon aircon starts to be demanded) all possible steps to reduce aircon load should be taken otherwise a significant fuel consumption/CO_2 increase will result. These measures could include heat-to-cool, solar reflective glazing/paint
Solar panels	<1.5% benefit given typical bus surface area. May be considered in conjunction with solar load reduction as above
Thermal phase change materials/heat storage tank	These store coolant heat to ensure engine is hot next time it starts. For typical bus operating cycle there is unlikely to be much opportunity for benefit since bus spends most of its time hot and operating
Automated manual transmissions	Not suitable for bus use due to poor shift quality leading to poor passenger comfort and durability
Eco-roll freewheel	No significant periods of coast down in MLTB. May be suited to coach application
LPG	Tank to wheels penalty, offset by small WTT benefit over CNG, leading to neutral WTW compared to diesel (source CONCAWE)

Technologies were excluded where they were considered unsuitable for bus use or were expected to give < 2% CO_2 benefit (4/4)

Technology Description	Comments
Dual fuel CNG or biomethane engines	Duel fuel technology such as Hardstaff or CAP where diesel fuel system is retained to provide a small quantity of diesel injection to ignite gas. However, at light loads (<30% of maximum torque) these systems tend to switch out of gas mode and run fully diesel, hence this technology is expected to give limited benefits for urban bus cycles
Electrolysed water feeding hydrogen to co-fuel conventional diesel ICE	No evidence of proper tests/trials allowing for energy consumed in electrolyser
FAME – 1st generation biodiesel	Considered as part of baseline fuel at B5% level as EN590 spec allows up to 7%. Significant concerns over storage stability and engine durability at blend rates above that
GTL fuels (gas to liquid Fischer Tropsch process)	Using NG as feedstock to produce liquid fuel has no WTW CO_2 benefit compared to burning NG direct which is already a poorer WTW situation than diesel. If successfully developed an implemented, CCS may reduce CO_2 emissions from this process.
Coal to liquid	Niche process (mainly South Africa) which has strong WTW CO_2 penalty. If successfully developed an implemented, CCS may reduce CO_2 emissions from this process.

Benefits of up to 5% reduction in fuel consumption are claimed for fuel additives, based on a number of physical mechanisms

- Claims of fuel consumption improvements based on fuel additives are common. For example, fuel consumption benefits have been claimed for bus fleets using Energenix
  - Energenix contains metallic nanoparticles, including cerium oxide, which act as catalysts during the combustion process
- Fuel additives aim to produce fuel consumption benefits based on a number of mechanisms:

Suggested Mechanism	Comment	Potential effect (% Fuel consumption reduction)
Detergency	Clean-up additives reduce deposits in engine including FIE. Further ‘keep clean’ functionality.	Initial positive response maintained by keep-clean functionality; < 3%
Combustion improvements	Improvements in combustion phasing, such as advanced timing, may have positive impact on suitable engines. Unlikely that completeness of combustion (already >>99% efficient) will be substantially modified	<2%
Emissions reduction	Combustion changes may have positive impacts on NOx and PM simultaneously.	N/A
Cetane improver in carrier	Addition of an additive carried in a high cetane base may lead to advanced timing (as above), if the carrier volume is large enough	<2%

A number of external factors can influence fuel consumption during a fleet trial

- Actual mechanisms for the reduction of fuel consumption in fleet trials could also include:

Probable Mechanism	Comment	Potential effect (% Fuel consumption reduction)
Detergency	Reduces or eliminates existing deposits in engine	<3%
Placebo effect	Knowledge of the presence of a fuel additive influences driver behaviour, positively impacting observed FC; Procedural: e.g: Additive added with oil change leading to decreased friction and improved FC	Up to 5%
Poor and unmatched cohorts	With additive and without additive studies conducted on low sample sizes and with fleets that are not properly matched; variations in the base fuel used during the studies	Possibly >5%, but equal chance of negative effect
Changes in driving conditions	Variations in traffic conditions, route, ambient conditions (temperature, pressure, humidity), driver between additised and unadditised studies	Possibly >5%, but equal chance of negative effect
Experimental sensitivity	Engine test bed can give test-to-test CO_2 measurement repeatability of ~0.5%, climate controlled chassis dyno testing 1%, test track 2%-3% accuracy. For the reasons quoted above, in-service tests would be expected to have greater uncertainty in their results, could be 5% or more	Uncertainty on measured effects may be ± >5%

Scientifically designed double blind tests would be required to confirm any unique effect of fuel additives on fuel consumption

- While fuel consumption benefits are being regularly quantified during in-use studies, it is not currently possible to unequivocally attribute these benefits to the sole action of a fuel additive
  - Fuel additives are therefore not included in this study
- Ricardo would recommend the use of the following test regime to produce evidence of the effect of fuel additives:
  - Transient engine dynamometer testing
    - Reducing variation in test conditions; eliminating the influence of the driver
    - Monitoring combustion parameters and emissions
  - Use of 4 nominally identical engines: 2 aged and 2 new
    - To examine the clean up effects of the fuel additive
    - To examine engine-to-engine variability
  - Use of fixed baseline fuel
    - Fixed batch tested with and without additive
    - Fixed batch tested with additive carrier only
  - Use of alternative baseline fuels
    - Screening to assess any fuel dependency on observed additive performance

Good operational practice can also make a significant contribution to reducing fuel consumption

- Some technologies or "operational techniques" have not been explicitly included within the study, but represent what might be considered "best practice". These are described in this "Housekeeping" section:
  - **Low rolling resistance tyres** – have already been mentioned and where possible should be used or offered by the tyre management contractor, where possible within the constraints of kerb-strike resistance requirements
  - **Tyre pressure management** – tyres should be run at optimal tyre pressure to ensure safety, durability and efficiency. It is assumed this is monitored by bus operators by regular checking but if necessary technological solutions such as tyre pressure monitoring systems should be specified to ensure compliance
  - **Driver training** (such as SAFED – see overleaf) – many bus operators already have driver training schemes in place – the challenge with driver training based improvements in fuel economy is how to avoid the benefit decaying as the driver "forgets" the training. Introduction of any new "fuel saving" technology should be accompanied by training to ensure drivers get the best performance out of the systems
  - **Driver advisory systems** can help to maintain "learned" fuel saving behaviour as the training fades into the driver's memory

Driver Training has been shown to give fuel consumption benefits in the bus industry

- Driver behaviour is an important contributor to achieving reduced fuel consumption / CO_2, through (example):
  - Correct selection of gear to keep engine operating at optimum speed/load
  - Well regulated driving without aggressive acceleration / deceleration events
- For HGVs driver training schemes such as SAFED have produced meaningful benefits of the order of 10%. Although “training decay” can occur, electronic aids, crib sheets and/or vehicle features (e.g. shift lights) can help to maintain effectiveness
- For buses, typically fitted with torque converter automatic transmissions with topographic shift point optimisation, the driver's influence on gear shift is minimal so less opportunity is available for saving, although regulated driving (smooth acceleration / deceleration) is still effective
- Large scale operators of hybrid fleets will typically engage in driver training to ensure they are driving the hybrid vehicles in the best way
- For these reasons, driver training has not been included as a technology. However it is clear that training leading to “driving best practice” for any vehicle type is a good “housekeeping” measure and an important tool in the reduction of both fuel costs and CO_2 emissions

Picture source: SAFED logo; GreenRoad app http://greenroad.com/uk/tour/ ; ZF Ecolife with Topodyn http://www.youtube.com/watch?v=9XbpUdnyvi4

Careful selection of vehicle specification can also make a significant contribution to reducing fuel consumption

- It is clear that ancillary loads on the engine make a significant contribution to fuel consumption and CO_2, and should be reduced wherever possible
- In specifying a new bus, "best practice" could be:
  - Specify low energy lighting (LED) and low energy installed equipment (CCTV, ticket machines etc.). If these are not readily available, challenge suppliers to address this
  - Resist the push to fit saloon air conditioning, instead specify passive technologies to minimise heat build up in the cabin. A saloon air conditioning system of 18kW installed capacity consumes similar power levels as it takes to propel a DD bus at 37mph
  - Passive technologies could include solar reflective glazing and/or paint
  - Investigate the applicability of solar PV to reduce alternator loading
  - Optimise vehicle electrical layout design to minimise losses between alternator, battery, starter and equipment

Reduction of bus idling will contribute to reducing fuel consumption and CO_2 emissions

- Reduction of unnecessary idling is a key theme in reducing CO_2 emissions of any vehicle (hence the proposal for stop-start systems) and this should extend to reduction of depot idling. Operator experience shows that buses are idled in depot for a number of reasons:
  - To ensure vehicles will definitely start (especially the case for older fleets) and not form a “logjam” in a crowded depot during the morning peak roll-out
  - To warm up the saloon on cold days
  - To charge battery and air systems
- Many depots are subject to space constraints which preclude the provision of dedicated vehicle parking bays. However where possible the provision of discrete bays with shore supply of power and air should be considered for new depot builds. This would have a number of benefits:
  - Assured start – battery always fully charged – provision of starter/charger
  - Air supply charged from shore supply
  - Engine preheat for cold weather
  - No need to idle engine – start up and drive

Contents

Technology packages have been selected to give a range of benefits and technology prices(1/2)

- Technology packages were selected by Ricardo evaluation of technology combinations that could function together and would give a range of CO_2 benefits
- The effect of each package on tailpipe CO_2 emissions has been assessed to give an estimate of potential GHG emissions saving
  - The assessment has been based on Ricardo’s development experience and simulation and test databases
- In general, CO_2 benefits for groups of technologies is not the sum of the benefits of the constituent parts, but may be less than this due to interactions and the fact the different technologies address the same inefficiency
- The payback time for each package is also assessed without BSOG or GBF
- Technology packages presented were agreed with the LowCVP bus working group following a project meeting on 31 August 2012

The stop start package is estimated to give 23% CO_2 benefit for around £3000 increased cost

Technology Package 1

- **Description:**
  - Smart ancillaries (compressor and alternator), stop start and pneumatic booster system are included in this package
  - Technologies were selected to give low payback + moderate benefits
- **CO_2 Benefit:**
  - Predominantly coming from stop-start to eliminate idles wherever possible. Smart ancillaries allow energy recovered in overrun/braking to run air and battery systems, maximising engine-off opportunities. Note CO_2 benefit is assumed to be not directly additive, since in low energy manoeuvres recovered energy may not be available for the ancillaries
- **Technology Price:**
  - Technology cost compared to the comparative diesel bus based on stop start 24V system cost + Knorr Bremse EAC estimated costs
- **Maintenance Cost:** increased starter motor maintenance
- **Payback period**: calculated with no subsidies

Single Deck	SD
WTW CO_2 Benefit (%)	21
Technology Price (£)	3000
Maintenance Cost (£)	500
Payback Period (Years)	0.2

Double Deck	DD
WTW CO_2 Benefit (%)	21
Technology Price (£)	3000
Maintenance Cost (£)	500
Payback Period (Years)	0.1

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12.

Source: .

The mild hybrid package is estimated to give around 22% CO_2 benefit for around £7500 increased cost

Technology Package 2

- **Description:**
  - Smart ancillaries (compressor and alternator) are combined with mild hybrid technology to give moderate benefits and payback
- **CO_2 Benefit:**
  - Predominantly coming from mild hybrid allowing effective energy recovery on accel-decel cycles. The hybrid system is focussed predominantly on recycling braking energy to the ancillaries. Note CO_2 benefit is assumed to be not directly additive, since in low energy manoeuvres recovered energy may not be available for the ancillaries
- **Technology Price:**
  - Technology cost compared to the comparitive diesel bus based on mild hybrid 48V system cost + Knorr Bremse EAC estimated costs
- **Maintenance Cost:** No change in Maintenance costs expected
- **Payback period**: calculated with no subsidies

Single Deck	SD
WTW CO_2 Benefit (%)	22
Technology Price (£)	7100
Maintenance Cost (£)	-
Payback Period (Years)	0.7

Double Deck	DD
WTW CO_2 Benefit (%)	22
Technology Price (£)	7500
Maintenance Cost (£)	-
Payback Period (Years)	0.5

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12.

Source: .

Flywheel hybrid with stop start benefit is estimated to give around 24% CO_2 reduction with a cost of £16 400

Technology Package 3

- **Description:** Flywheel hybrid is combined with stop start to increase benefits available from flywheel hybrid system
- **CO_2 Benefit:** Flywheel system recovers energy while bus is in motion, while the stop start system reduces fuel use at idle where ancillary loads permit. CO_2 benefit is based on Ricardo simulation of Flywheel hybrid systems for bus application
- **Technology Price:** Technology cost is the sum of flywheel hybrid and stop start costs
- **Maintenance Cost:** Flywheel hybrid reduces brake maintenance costs
- **Payback period**: calculated with no subsidies

Single Deck	SD
WTW CO_2 Benefit (%)	24
Technology Price (£)	16400
Maintenance Cost (£)	-60
Payback Period (Years)	1.5

Double Deck	DD
WTW CO_2 Benefit (%)	24
Technology Price (£)	16400
Maintenance Cost (£)	-60
Payback Period (Years)	1.0

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12.

Source: .

Series Hybrid with AD biomethane fuelled engine gives a high WTW CO_2 benefit

Technology Package 4

- **Description:** Series hybrid is combined with a biomethane fuelled engine to give a high WTW CO_2 benefit
- **CO_2 Benefit:** Series hybrid TTW CO_2 benefit of 40% is combined with WTW CO_2 reduction of a diesel pilot AD biomethane fuelled engine
- **Technology Price:** Technology price for this combination is high due to the high cost of both technologies
- **Maintenance Cost:** Reduction in brake maintenance costs due to wear reduction facilitated by regenerative braking, additional gas engine maintenance costs
- **Payback period**: calculated with no subsidies

Single Deck	SD
WTW CO_2 Benefit (%)	125
Technology Price (£)	120000
Maintenance Cost (£)	440
Payback Period (Years)	9.8

Double Deck	DD
WTW CO_2 Benefit (%)	125
Technology Price (£)	135000
Maintenance Cost (£)	440
Payback Period (Years)	7.0

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12.

Source: .

Technology packages have been selected to give a range of benefits and technology prices

- Selected technology packages and their benefits are shown in the table below
  - Payback times are shown without subsidies

Package number	**Description**	**Technology price (£)**		**WTW CO_2 benefit (%)**		**Payback time (years)**	
		SD	DD	SD	DD	SD	SS
1	Stop start, PBS and smart ancillaries	3000	3000	18	18	0.3	0.2
2	Mild hybrid and smart ancillaries	7100	7500	22	22	0.7	0.5
3	Flywheel hybrid and stop start	16400	16400	24	24	1.5	1.0
4	Series hybrid with diesel pilot biomethane engine	120000	135000	125	125	0.3	0.2

Assumptions: 40000 miles pa both SD and DD; fuel consumption 6mpg SD , 8mpg DD; base diesel fuel price 50 ppL; base CNG, CBG price 60.3p/kg (prices do not include duty and BSOG); BSOG and fuel duty rates as at 1.9.12.

Contents

The suitability of selected technologies for other commercial vehicle applications was assessed

- Technologies identified for buses with applicability in other sectors
  - Technologies with applicability across most sectors are highlighted

Technology	**Vehicle suitability**					
	Bus	Coach (Intercity)	Heavy Duty Truck (Intercity)	Medium Duty Truck (Delivery)	Utility Truck (Powered body)	Off Highway (Tractor, excavator)
Lightweighting	Yes	Yes	Yes	Yes	Yes	No (often ballasted for stability)
Smart ancillaries	Yes	Yes	Yes	Yes	Yes	Possibly
Rankine EHR	Poor cost benefit	Yes	Yes	Poor cost benefit	Poor cost benefit	No
IVT	Yes	Unlikely due to constant speed operation		Possibly	Possibly	No
Stop start/mild hybrid	Yes	Unlikely due to constant speed operation		Yes	No	No
Full hybrid	Yes	Unlikely due to constant speed operation		Yes	Yes	Yes
Flywheel	Yes	Unlikely due to constant speed operation		Yes	Possibly	Yes
Pneumatic booster	Yes	Yes	Yes	Yes	Yes	Yes

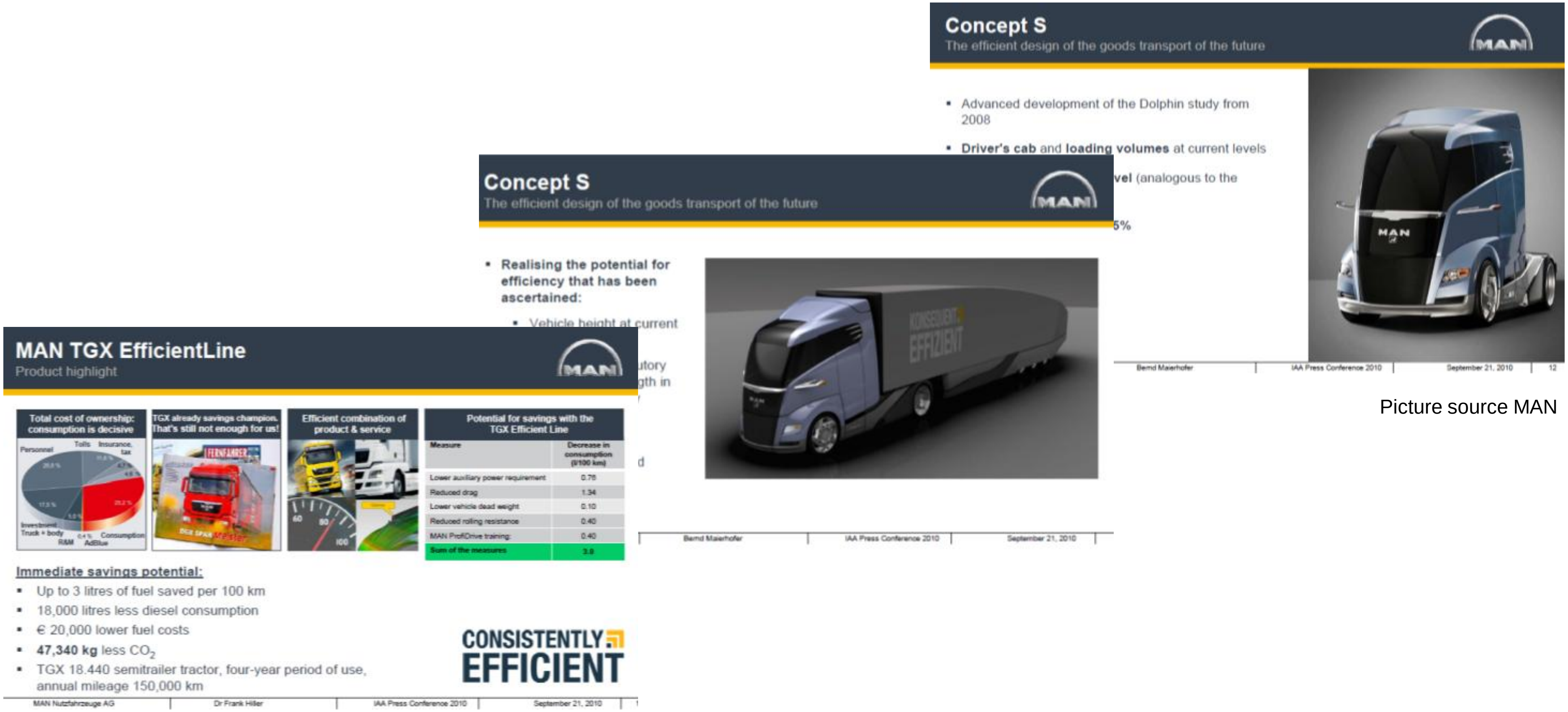
Technologies with a range of potential applications could achieve economies of scale or synergies with other sectors

- Technologies identified for buses with applicability in other sectors
  - Technologies with applicability across most sectors are highlighted

Technology	Vehicle suitability					
	Bus	Coach (Intercity)	Heavy Duty Truck (Intercity)	Medium Duty Truck (Delivery)	Utility Truck (Powered body)	Off Highway (Tractor, excavator)
BEV	Yes	No	No	Yes	Possibly (small vehicles)	No
Trolley bus	Yes	No	No	No	No	No
CNG Stoich/lean	Yes	Yes	Yes	Yes	Yes	Possibly
LNG diesel pilot	Possibly	Possibly	Yes	Possibly	Possibly	No
Biomethane	Yes	Yes	Yes	Yes	Yes	Possibly
E95/Bio DME	Yes (niche)	Possibly (niche)	Possibly (niche)	Possibly (niche)	Possibly (niche)	Possibly (niche)
Hydrogen FC/ICE	Yes (niche)	Possibly (niche)	Unlikely	Possibly (niche)	Possibly (niche)	Unlikely
BTL/HVO	Yes	Yes	Yes	Yes	Yes	Yes

Focus for HGV development is on a broad range of technologies that may not be applicable to the bus industry

- HGV development effort is currently focused on a broad range of technologies including aerodynamics, ancillary power, rolling resistance, lightweighting and driver training
- The figures below show an example strategy presented by MAN at IAA Show 2012



Concept S

The efficient design of the goods transport of the future

- Advanced development of the Dolphin study from 2008
- **Driver's cab** and **loading volumes** at current levels
- **vel** (analogous to the
- 5%

Bernd Maierhofer | IAA Press Conference 2010 | September 21, 2010 | 12

Concept S

The efficient design of the goods transport of the future

- **Realising the potential for efficiency that has been ascertained:**
  - Vehicle height at current
  - utory
  - gth in
  - d

Bernd Maierhofer | IAA Press Conference 2010 | September 21, 2010

MAN TGX EfficientLine

Product highlight

Total cost of ownership: consumption is decisive

TGX already savings champion. That's still not enough for us!

Efficient combination of product & service

Potential for savings with the TGX Efficient Line

Measure	Decrease in consumption (l/100 km)
Lower auxiliary power requirement	0.78
Reduced drag	1.34
Lower vehicle dead weight	0.10
Reduced rolling resistance	0.40
MAN ProfiDrive training:	0.40
Sum of the measures	3.0

Immediate savings potential:

- Up to 3 litres of fuel saved per 100 km
- 18,000 litres less diesel consumption
- € 20,000 lower fuel costs
- **47,340 kg** less CO_2
- TGX 18.440 semitrailer tractor, four-year period of use, annual mileage 150,000 km

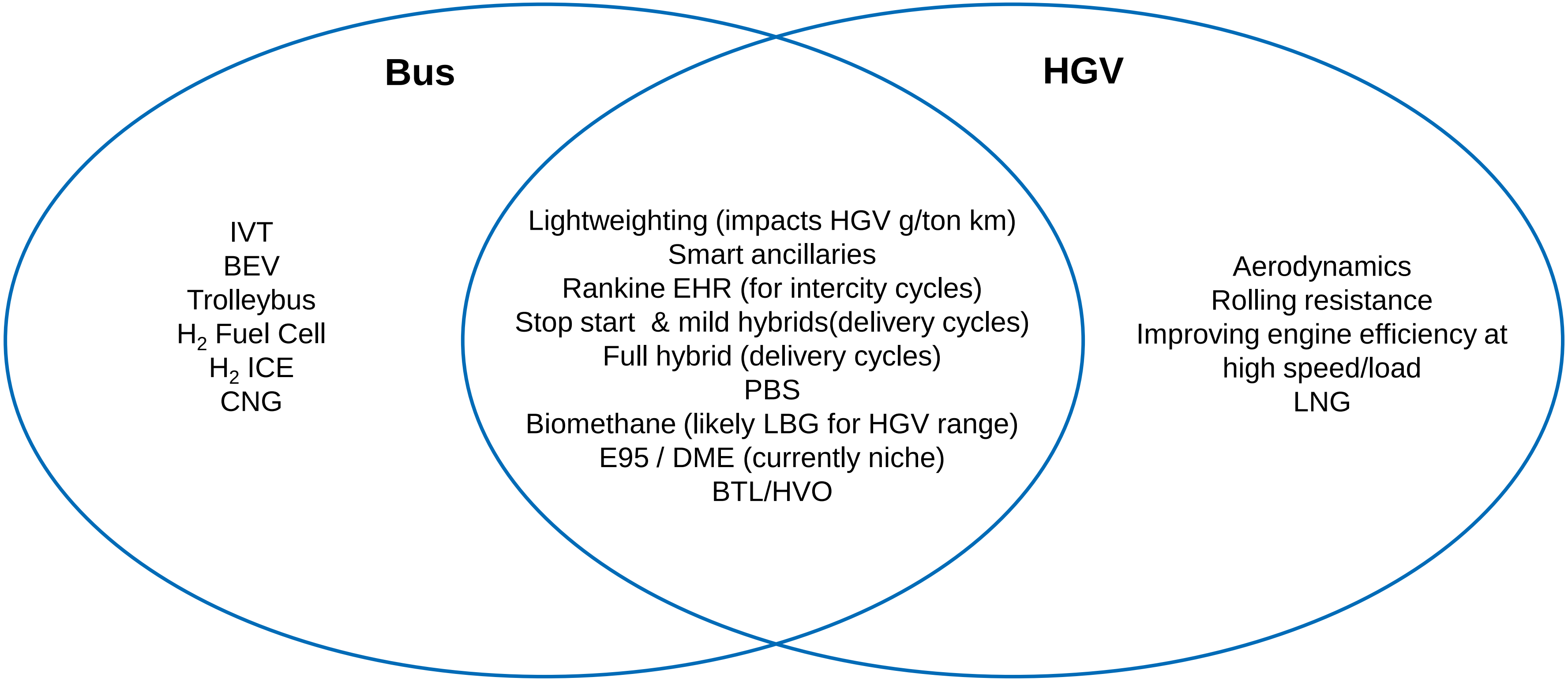
CONSISTENTLY EFFICIENT

MAN Nutzfahrzeuge AG | Dr Frank Hiller | IAA Press Conference 2010 | September 21, 2010

Picture source MAN

Where selected technologies are not applicable to other sectors, development work will be needed from within the bus industry

- Some of the technologies proposed for buses some overlap with HGVs, especially smart ancillaries and some hybridisation routes
- Aerodynamics is a dominant HGV trend that will have limited applicability to buses because of low speed duty cycle, but will have applicability to coaches



Bus

IVT
BEV
Trolleybus
H_2 Fuel Cell
H_2 ICE
CNG

Lightweighting (impacts HGV g/ton km)
Smart ancillaries
Rankine EHR (for intercity cycles)
Stop start & mild hybrids(delivery cycles)
Full hybrid (delivery cycles)
PBS
Biomethane (likely LBG for HGV range)
E95 / DME (currently niche)
BTL/HVO

HGV

Aerodynamics
Rolling resistance
Improving engine efficiency at high speed/load
LNG

Contents

Ricardo has prepared low CO_2 technology roadmaps for buses in the two timescales 2012-2020 and 2020-2050

- These roadmaps illustrate when technologies expected to give greater than 2% fuel consumption reductions are likely to enter the UK bus market, their technology development within this market, and whether the technologies are likely to be superseded in the future
- **2012-2020: near term roadmap**
  - These roadmaps show timeframes for the introduction of individual low carbon technologies
    - These roadmaps consider expected development timescales for the technologies and do not attempt to predict levels of uptake
  - Likely introduction timeframes for the technology packages developed will be considered in the light of these roadmaps
    - Technologies that are critical to the introduction of these packages will be highlighted
- **2020-2050: long term roadmap**
  - This roadmap considers the future development of bus technology based on more general technology trends and illustrates headline technologies
  - The roadmap draws on and is compatible with the Automotive Council CVOH (commercial vehicle and off highway) roadmap

Bus market drivers are a combination of commercial and legislative factors

Government

- Subsidy landscape
  - Fuel subsidy
    - BSOG
  - Technology based subsidies
    - Green Bus Fund, Regional subsidies
- Legislation
  - Emissions (Euro VI,2013)
  - Biofuels (eg. RTFO)
  - Disabled access, Noise

Profitability

- Patronage
  - Increasing bus desirability
  - Passenger comfort
- Total cost of ownership
  - Operating cost (fuel, service / maintenance)
  - Capital cost

Bus market drivers

Operational requirements

- Reliability
- Durability
- Vehicle utilisation (% downtime)
- Safety
- Driver comfort/working environment
- Depot logistics, refuelling infrastructure
- OEM service support

Bus supply chain

- Low volumes
  - Economies of scale challenging, leading to relatively higher technology cost
- Localised markets

Source: Ricardo Analysis

In the longer term, planned legislation to mandate CO_2 emissions for heavy duty vehicles will provide more focus on fuel consumption

- The EC is investigating measures to reduce CO_2 emissions from Heavy duty vehicles, including passenger transport
  - The 2011 EC White Paper 'Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system' sets an objective to reduce transport GHG emissions by 60% in 2050 compared to 1990 (as a contributor to reducing emissions from all sectors by 80-95%)
- An initial stakeholder consultation has been held, involving HDV manufacturers, component suppliers, transport operators, logistics companies and NGOs
- Methods to assess CO_2 emissions from HDVs are under investigation
    - Current emissions test are on an engine basis
    - There is no unified measurement scheme for HDV on a vehicle basis in Europe
    - Approach under consideration includes model based simulation of the whole vehicle and component (engine) testing
    - Finalisation of HDV CO_2 measurement and certification method is expected in 2014

Source: European Commission Climate Action (http://ec.europa.eu/clima/events/0054/index_en.htm) EC white paper Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0144:EN:NOT)

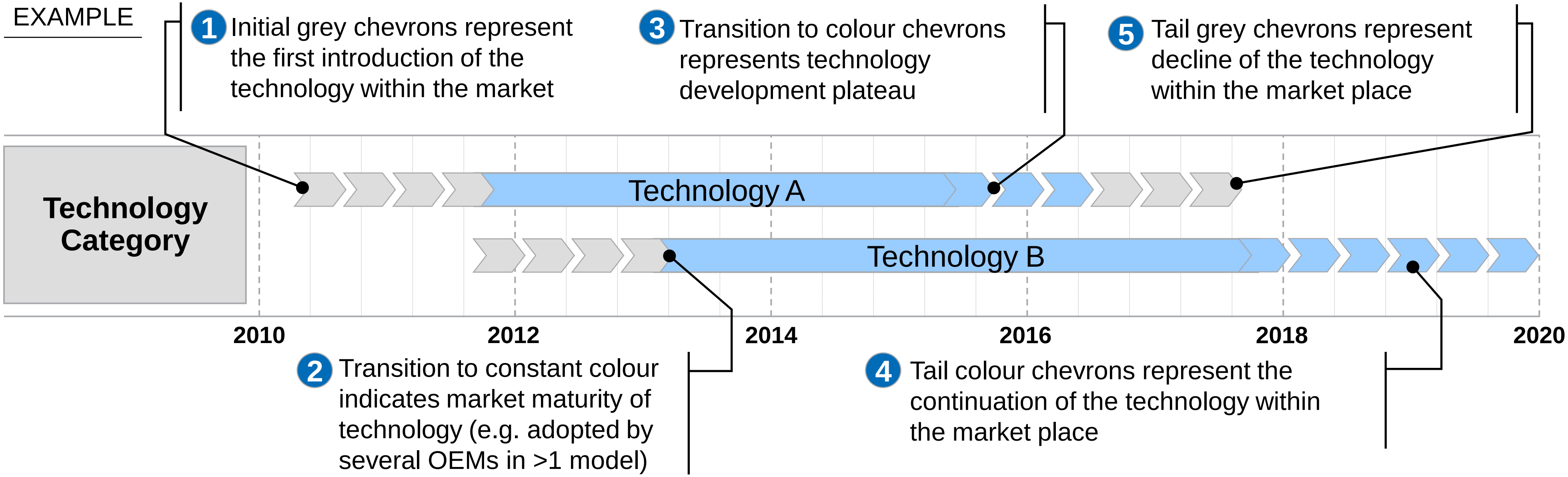
Contents

Colours, shapes and symbols are used in the technology roadmaps to convey information

Understanding Technology Roadmaps

- The following technology roadmaps aim to identify trends in vehicle technology coming into the market place
- The following description explains the use and meaning of colour, shading and symbols that can be found on the roadmaps
- Timings are indicative of expected progress in the **UK bus industry**

EXAMPLE



① Initial grey chevrons represent the first introduction of the technology within the market

② Transition to constant colour indicates market maturity of technology (e.g. adopted by several OEMs in >1 model)

③ Transition to colour chevrons represents technology development plateau

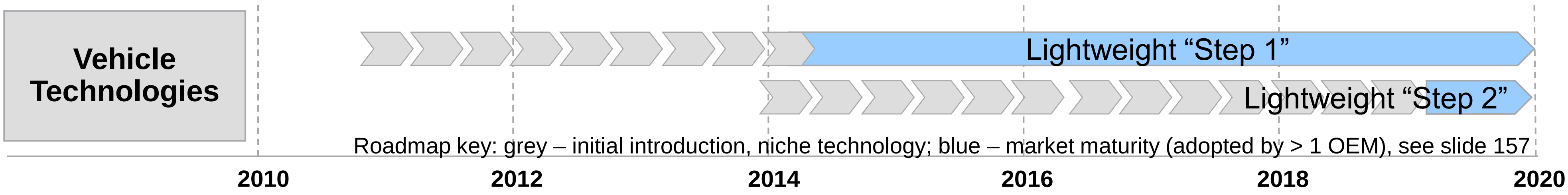
④ Tail colour chevrons represent the continuation of the technology within the market place

⑤ Tail grey chevrons represent decline of the technology within the market place

Source: Ricardo

Few vehicle technologies influence bus fuel consumption due to the lower speed duty cycle

Vehicle Technologies Roadmap for UK Buses to 2020



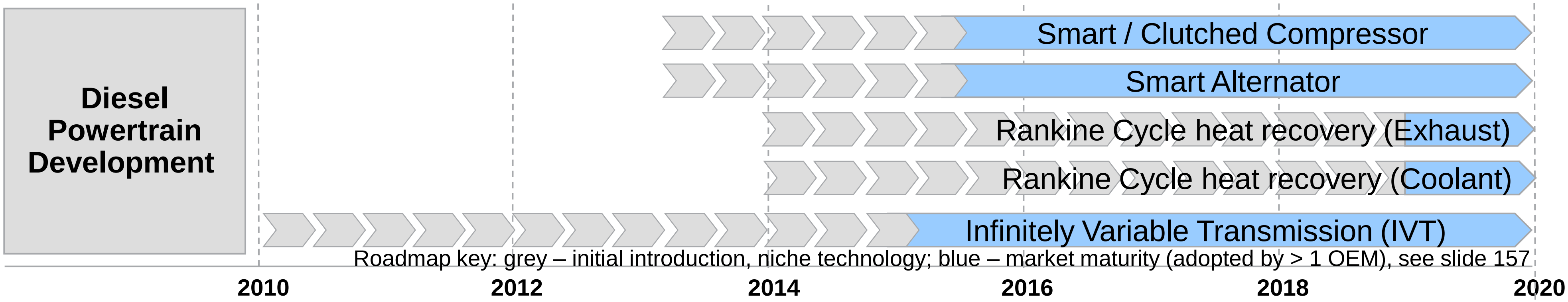
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Few vehicle technologies influence bus fuel consumption due to the lower speed duty cycle
  - Measures to reduce aerodynamic drag have little effect on urban bus fuel consumption
  - Reducing tyre rolling resistance is a continuous improvement activity, but is limited by bus specific durability requirements (eg kerb strike durability)
- Materials and technologies required for Step 1 lightweighting (bus structure optimisation, high strength steels and high grade aluminium) are currently in use in other applications (i.e. passenger car body, closures and chassis systems)
  - The introduction of Step 1 technologies requires redesign and engineering of the bus chassis but could be implemented as part of a model update
- Step 2 lightweighting includes introduction of new Tier 1 lightweight powertrain, axle (aluminium), wheels, tyres and brakes, Aluminium chassis frame, Polycarbonate / SMC exterior panels, New lightweight seating (similar to aerospace industry trend)
  - The introduction of step 2 technologies will require significant investment from the Tier 1 axle suppliers (Dana, ZF) to produce lightweight systems suitable for bus application. The timing of this will depend on demand from OEs and the subsequent economic conditions

Source: Ricardo analysis

Technologies to recover waste heat and reduce ancillary energy consumption are expected to be available for buses before 2020

Diesel Powertrain Roadmap for UK Buses to 2020



Diesel Powertrain Development

Smart / Clutched Compressor

Smart Alternator

Rankine Cycle heat recovery (Exhaust)

Rankine Cycle heat recovery (Coolant)

Infinitely Variable Transmission (IVT)

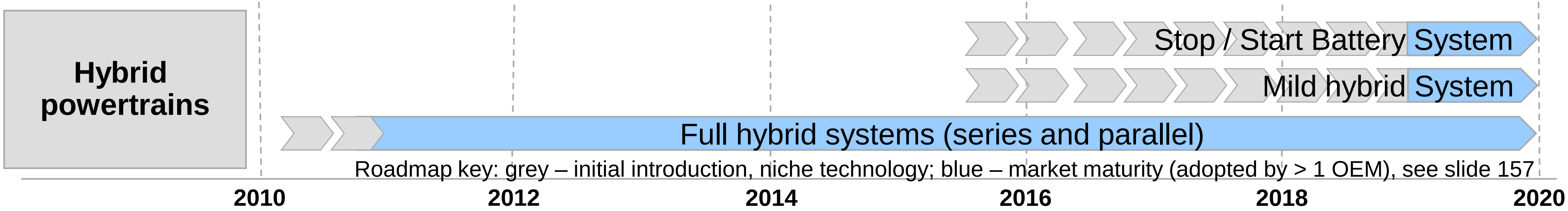
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Smart Ancillaries such as Smart / Clutched Compressors and Smart Alternators which run on demand or on overrun only are currently mainstream in other sectors
  - The Knorr Bremse EAC has been developed for HGV
  - These technologies could be mainstream for UK buses by around 2017, based on expected development time for bus application
- Rankine cycle heat recovery technology technology has been validated and is on the market for stationary power generation engines
  - Systems for mobile applications such as passenger car and HGV are currently in development
  - Validation of system robustness for bus operation is required
- Torotrak IVT is currently licensed by Allison for bus application
  - Development is required for durability in real world conditions

Source: Ricardo analysis

Full hybrids are now a mature technology, mild hybrid and stop start may appear in the bus market by 2020

Alternative Powertrain Roadmap for Buses to 2020

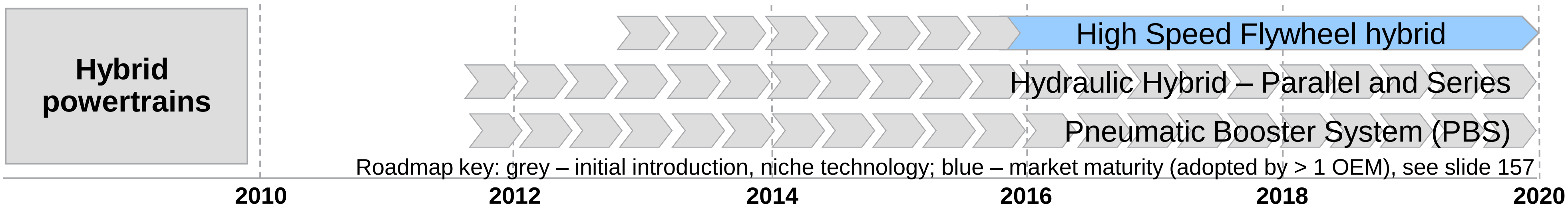


- Stop / Start systems are on the market for HGVs and buses in other markets (eg Mercedes Citaro city bus)
- Development is needed to ensure engine durability with increased starts and manage vehicle level integration, eg. bus auxiliary loads during engine shut down
- mild hybrid systems have yet to be developed for buses
  - Development of major components (eg motor, inverter, battery) plus engine durability testing is required for bus application
- Full Hybrid Systems are relatively mature technologies, with sizeable numbers of hybrid buses now in operation in the UK
  - TfL has recently approved a contract to purchase 600 hybrid buses over the next four years, taking the number operating in London to 1000 by 2016
- Given the high initial costs for this technology, the take up by the UK bus industry is expected to remain dependent on available subsidies
  - Costs are expected to reduce gradually, but low volumes and diverse applications mean that economies of scale may be difficult to achieve in the commercial vehicle market

Source: Ricardo analysis, TfL http://www.tfl.gov.uk/corporate/media/newscentre/25748.aspx

Alternatives to battery hybrids, such as hydraulic or flywheel systems, could be introduced as a niche technology in the near future

Alternative Powertrain Roadmap for UK Buses to 2020



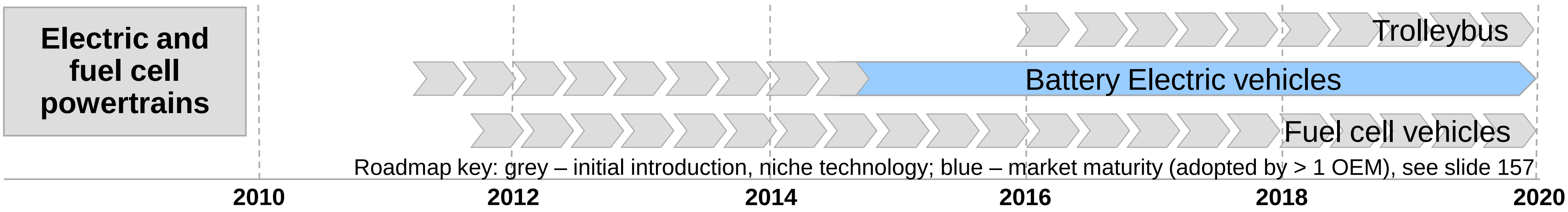
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- High speed flywheel systems are well suited to the stop start duty cycle of a bus
  - Flywheel hybrid systems for buses are under development by a number of companies
- A Hydraulic Hybrid bus demonstrator has recently been developed by the US freight transport authority (FTA)
  - The custom designed bus combined lightweighting with a series hydraulic powertrain to give significant fuel consumption reductions
- Hydraulic hybrid technology has also been trialled in other sectors, but is not currently available ‘off the shelf’
  - UPS conducted an operational trial involving 6 vehicles in 2009
  - Parker Hannifin has developed a refuse truck demonstrator for their Runwise system
  - Artemis digital displacement pump system has been implemented in a series hybrid passenger car application
- It is currently unclear whether hydraulic hybrids will gain widespread market acceptance, the technology therefore remains niche up to 2020 on this roadmap
- Pneumatic Booster Systems, such as those offered by Knorr Bremse are available for heavy duty application, but are currently not expected to become mainstream technologies for UK buses

Source: Ricardo analysis, UPS press release (http://pressroom.ups.com/Fact+Sheets/UPS+Uses+Technology+and+Operational+Efficiencies+to+Reduce+Fuel+Consumption+and+Emissions), Williams website (http://www.williamshybridpower.com/applications/buses/#/applications/go_ahead_group), Artemis website (http://www.artemisip.com/applications/on-road)

Battery electric buses are gaining poplarity due to their zero emissions at point of use

Alternative Powertrain Roadmap for UK Buses to 2020



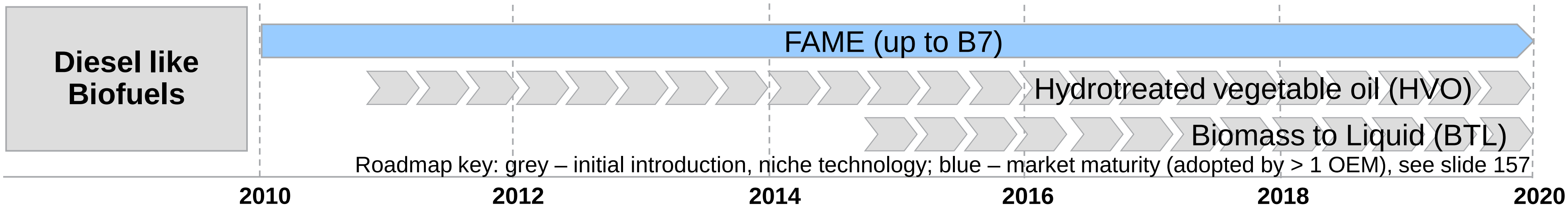
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Trolley buses, powered through overhead lines, are in use in a large number of cities worldwide
  - The WTW CO_2 benefits of these systems depend on the local electricity grid mix
  - UK Government funding was approved in July 2012 for a trolley bus system in Leeds, with construction planned to start in 2016
- There are a number of battery electric buses in use or planned in the UK, examples include:
  - Milton Keynes council has won funding from the green bus fund for electric buses: Arup, Wrightbus, Arriva, Arup, Mitsui, MKC, Wampfler, and Western Power have agreed to run a five year trial using inductive fast charging at points on the route
  - Coventry City Council has won Green Bus Fund funding for an electric park and ride system using a fast charge system, operating Optare Vera buses
  - Nottingham has been awarded Green Bus Fund funding for a fleet of eight electric buses, part funded by the Green Bus Fund
- Fuel cell bus trials in the UK continue, including:
  - FirstGroup operate hydrogen fuel cell buses on a central London route, part funded by the EU HyTEC project, and government funding has been agreed to support 10 hydrogen fuel cell buses in Aberdeen
- Reductions in fuel cell bus costs and development of a hydrogen refuelling infrastructure are necessary to encourage the introduction of this technology into the mass market

Source: Ricardo analysis, BBC news (http://www.bbc.co.uk/news/uk-england-leeds-18724776), Milton Keynes Council (http://cmis.milton-keynes.gov.uk/CmisWebPublic/Binary.ashx?Document=36470), bbs news (http://www.bbc.co.uk/news/uk-england-coventry-warwickshire-18420557), Nottingham City council (http://www.nottinghamcity.gov.uk/pressarchive/index.aspx?articleid=19565), Air Products (http://www.airproducts.co.uk/news/2012-07-06.htm), Scottish Government (http://www.scotland.gov.uk/News/Releases/2012/08/scottish-hydrogen-hub14082012)

Substitional biofuels such as HVO and BTL are expected to remain niche up to 2020 due to low supply volumes

Biofuels Roadmap for UK Buses to 2020

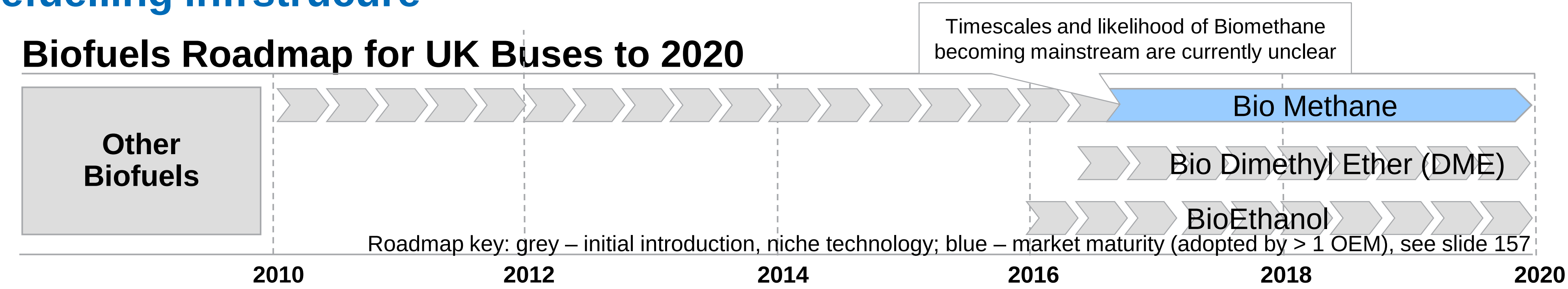


Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- UK pump diesel currently contains up to 7% FAME
  - The blend level of FAME is limited to B7 by compatibility with engine technology and OEM warranty
    - Any increase in this blend level would require support from engine manufacturers and Tier 1 suppliers (eg FIE suppliers)
  - The EC is planning to limit biofuel content made from crop based feedstocks to 5% up to 2020 [1]
  - Higher FAME blend levels are therefore not expected in this timeframe
- HVO is classified as a 1 ½ generation biofuel, and can be used in an unmodified diesel engine
  - Currently HVO is produced by Neste Oil at their refineries in Finland, Singapore and the Netherlands
  - Current production levels are less than 1% of total EU diesel market
  - This fuel is expected to remain a significant niche fuel up to 2020 due to low supply volumes
- 2nd generation fuels (BTL) can also be used in an unmodified diesel engines
  - Significant production of BTL is not expected until the timeframe 2025 – 2030 and may be delayed depending on technology advances and economic impact

Source: Ricardo analysis, Neste Oil, [1]Reuters (http://www.reuters.com/article/2012/09/17/us-eu-biofuel-idUSBRE88G0IL20120917)

Biomethane could become mainstream in the short term, but requires investment to provide fuel availability, distribution and refuelling infrstrucure



Biofuels Roadmap for UK Buses to 2020

Timescales and likelihood of Biomethane becoming mainstream are currently unclear

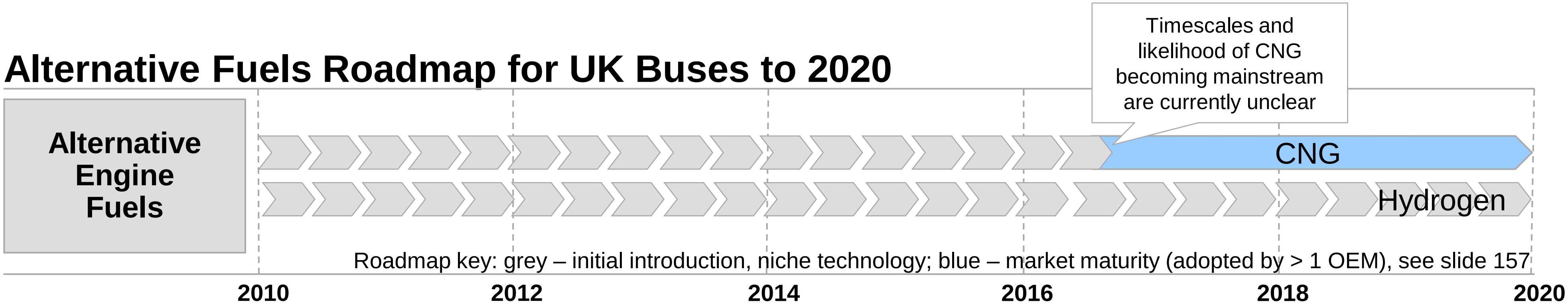
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Engines to burn biomethane are identical to those for CNG, and are mature technology available from a number of manufacturers
- The widespread use of Biomethane in the UK is limited by fuel availability (partly due to competition with use for electricity generation), distribution and refuelling infrastructure
  - The TSB low carbon truck programme will fund the installation and trial of a number of Biomethane refuelling station that could be used by bus fleets, however these are targeted at HGVs and not all will be conveniently located for bus fleets
  - GasRec currently supplies bio LNG to small captive fleets and plans to open it’s first strategic filling station on the M1 in 2013
  - The Gas Bus Alliance (GBA) supplies fossil natural gas, offseting a proportion of this fossil gas with grid injection of biomethane
    - GBA have supplied infrastructure and gas for several bus trials, including Thames travel and Reading Transport
- Vehicle trials of Bio-DME in Volvo trucks are currently underway in Sweden where bio-DME is produced from forestry waste by Chemrec as part of the EU BioDME programme
  - If Bio-DME were introduced in the UK, it is expected that it would be used for captive fleets
- Bioethanol (E95) can be burned in a modified diesel engine, with the addition of an octane improver
  - The necessary engine modifications have been demonstrated by Scania
  - A bioethanol fuelled bus trials have been undertaken in the UK, including Stagecoach in 2006, Nottingham 2008-2010
  - Ethanol has significantly lower energy density, reducing vehicle range and potentially increases fuel costs

Source: Ricardo analysis, GasRec (http://gasrec.co.uk/presentation.pdf) BioDME project website(http://www.biodme.eu/news/follow-the-progress-of-the-field-test), Nottingham Ehtanol bus trial (http://www.nctfleetlist.co.uk/php/fleet/includes/Ethanol.pdf), Bus and Coach magazine (http://www.busandcoach.com/newspage.aspx?id=921&categoryid=0)

CNG could reach a mass market in the UK with capital investment in refuelling infrastructure, but CO_2 benefits can be marginal

Alternative Fuels Roadmap for UK Buses to 2020



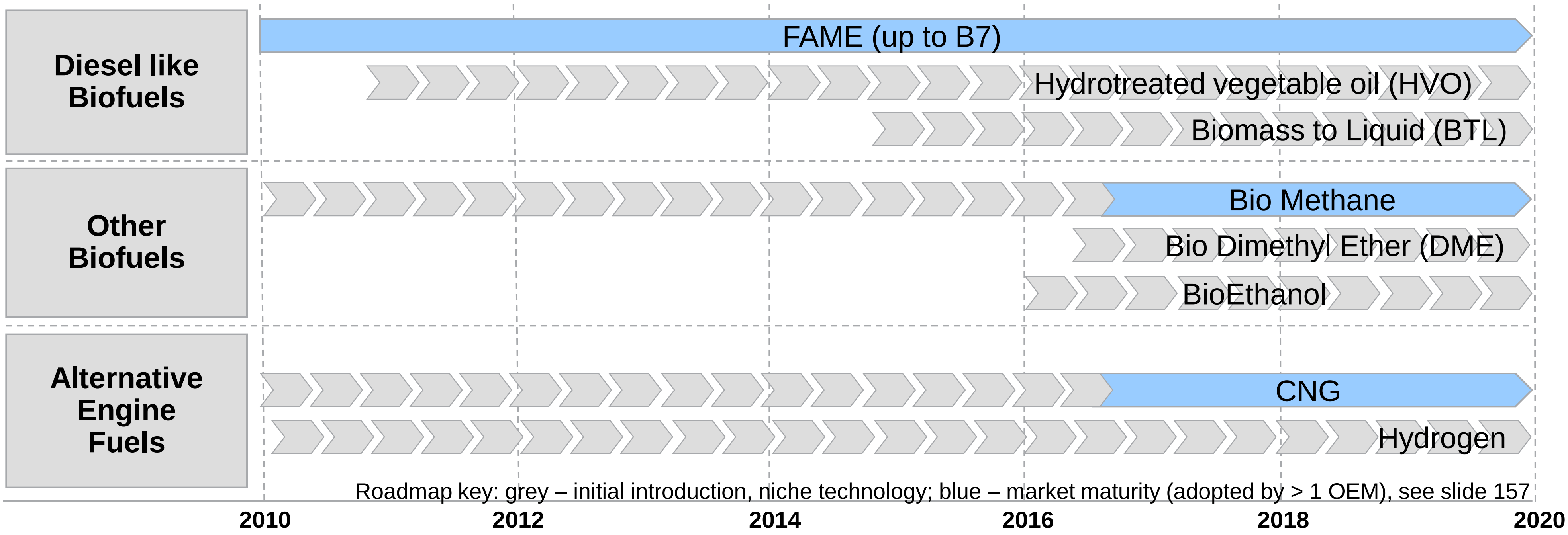
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Engine technology for CNG fuelled vehicles is mature and on offer from a number of manufacturers
- A number of bus fleets currently run on CNG worldwide, for example, in the US in 2012, approximately 20% of buses run on CNG or LNG
- In the UK in 2011, CNG buses made up 0.5% of the national bus fleet
  - Support from the Green Bus Fund has been gained for a growing number of CNG buses, for example Anglian buses have won funding for 13 gas buses for East Anglia, Arriva has won funding for 21 biomethane fuelled buses for operation around the country
  - Mass market uptake of this fuel in the UK requires capital investment in refuelling infrastructure
- Hydrogen can be used to fuel buses via both fuels cells and internal combustion engines
  - Hydrogen ICE buses have been demonstrated by MAN as part of the HyFLEET CUTE programme
  - There have been a significant number of hydrogen fuel cell bus trials (See alternative powertrain roadmap slide)
- Mass market introduction of hydrogen fuelled vehicles would require development of a distribution and refuelling infrastructure

Source: Ricardo analysis, American Fleet Transport Authority Factbook, NGVA statistics 2011, HyFLEET CUTE (http://www.global-hydrogen-bus-platform.com/Technology/HydrogenInternalCombustionEngines), Arriva press release 23 March 2012 (http://www.arriva.co.uk/arriva/en/media_centre/press_releases/2012/2012-03-23/)

While many biofuel and alternative options exist for buses, only CNG or biomethane have the potential for mass market penetration in the near term

Summary - Fuels Roadmap for UK Buses to 2020

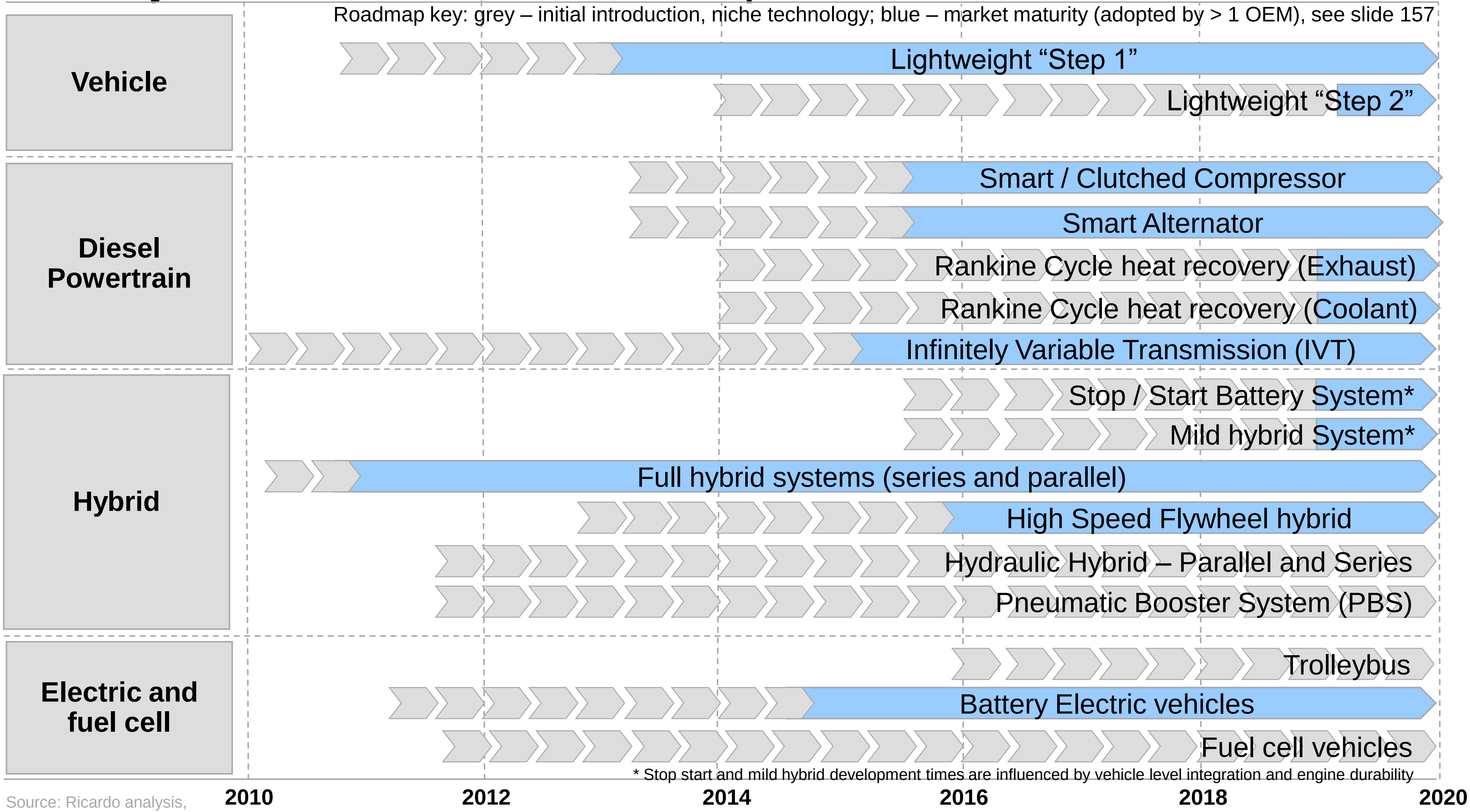


Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

Source: Ricardo analysis,

Many low carbon technologies require development for bus application

Summary - Vehicle and Powertrain Roadmap for UK Buses to 2020



Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

Vehicle
- Lightweight “Step 1”
- Lightweight “Step 2”

Diesel Powertrain
- Smart / Clutched Compressor
- Smart Alternator
- Rankine Cycle heat recovery (Exhaust)
- Rankine Cycle heat recovery (Coolant)
- Infinitely Variable Transmission (IVT)

Hybrid
- Stop / Start Battery System*
- Mild hybrid System*
- Full hybrid systems (series and parallel)
- High Speed Flywheel hybrid
- Hydraulic Hybrid – Parallel and Series
- Pneumatic Booster System (PBS)

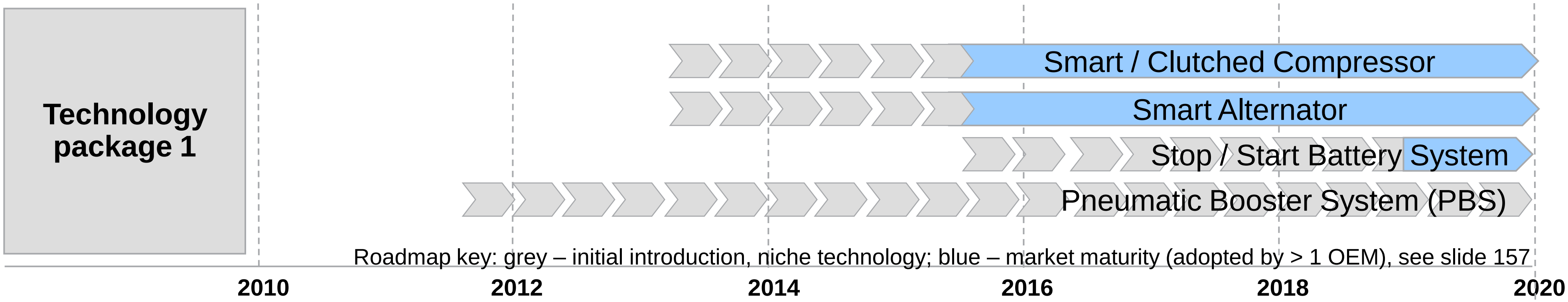
Electric and fuel cell
- Trolleybus
- Battery Electric vehicles
- Fuel cell vehicles

* Stop start and mild hybrid development times are influenced by vehicle level integration and engine durability

Source: Ricardo analysis,

Likely introduction timings for technology packages are presented based on expected time to market for components – Package 1

Package 1 Roadmap



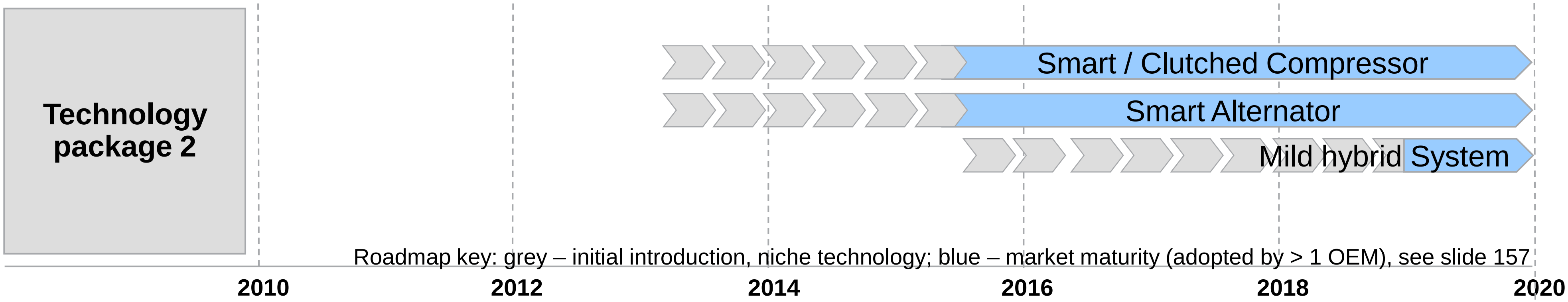
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Technology package 1 summary
  - Smart ancillaries (compressor and alternator), stop start and pneumatic booster system are included in this package
  - Technologies were selected to give low payback + moderate benefits
  - Earliest introduction expected ~2019
- Development of stop start technology for buses is a key enabler for the introduction of this package

Source: Ricardo analysis

Likely introduction timings for technology packages are presented based on expected time to market for components – Package 2

Package 2 Roadmap



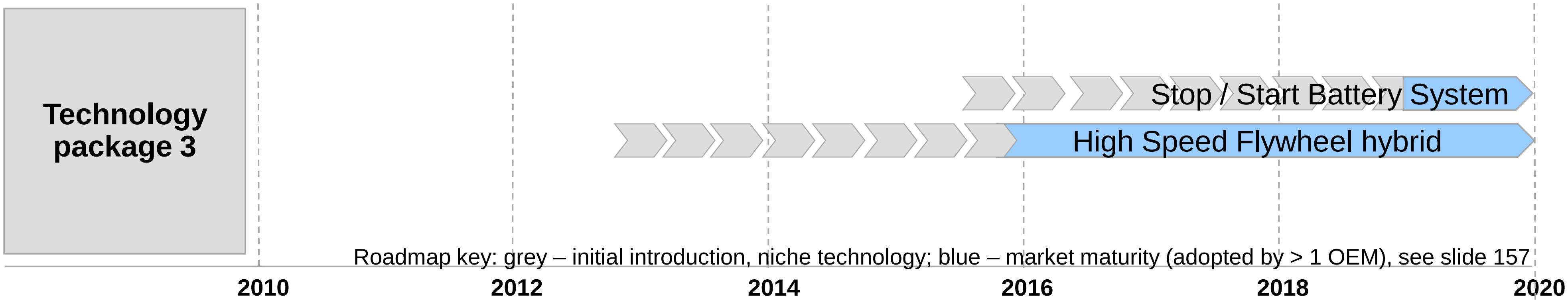
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Technology package 2 summary
  - Smart ancillaries (compressor and alternator) are combined with mild hybrid technology to give moderate benefits and payback
  - Earliest introduction expected ~ 2019
- Development of mild hybrid technology for buses is a key enabler for the introduction of this package

Source: Ricardo analysis

Likely introduction timings for technology packages are presented based on expected time to market for components – Package 3

Package 3 Roadmap



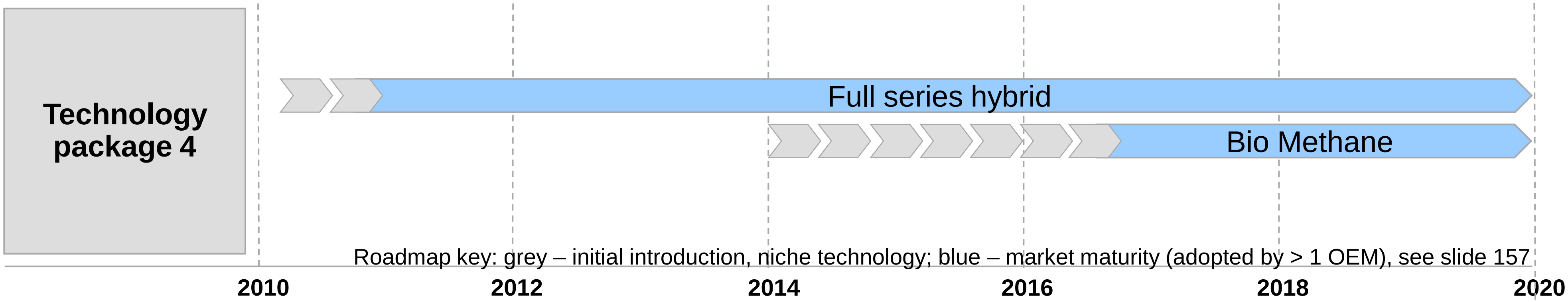
Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Technology package 3 summary
  - Flywheel hybrid is combined with stop start to increase benefits available from flywheel hybrid system
  - Earliest introduction expected ~ 2019
- Development of stop start technology for buses is a key enabler for the introduction of this package

Source: Ricardo analysis

Likely introduction timings for technology packages are presented based on expected time to market for components – Package 4

Package 4 Roadmap



Roadmap key: grey – initial introduction, niche technology; blue – market maturity (adopted by > 1 OEM), see slide 157

- Technology package 4 summary
  - Series hybrid is combined with a biomethane fuelled Lean Diesel pilot engine to give a high WTW CO_2 benefit
  - Lean Diesel pilot CNG Engine technology is currently not available in a bus engine in Europe
    - Westport currently supply a 15L HPDI engine to the US truck industry
    - The package could be introduced now with a lower efficiency SI engine
  - Fuel supply is currently niche, potentially limiting penetration of this technology package
- Technology package could be introduced now, with a lower efficiency SI CNG engine

Source: Ricardo analysis

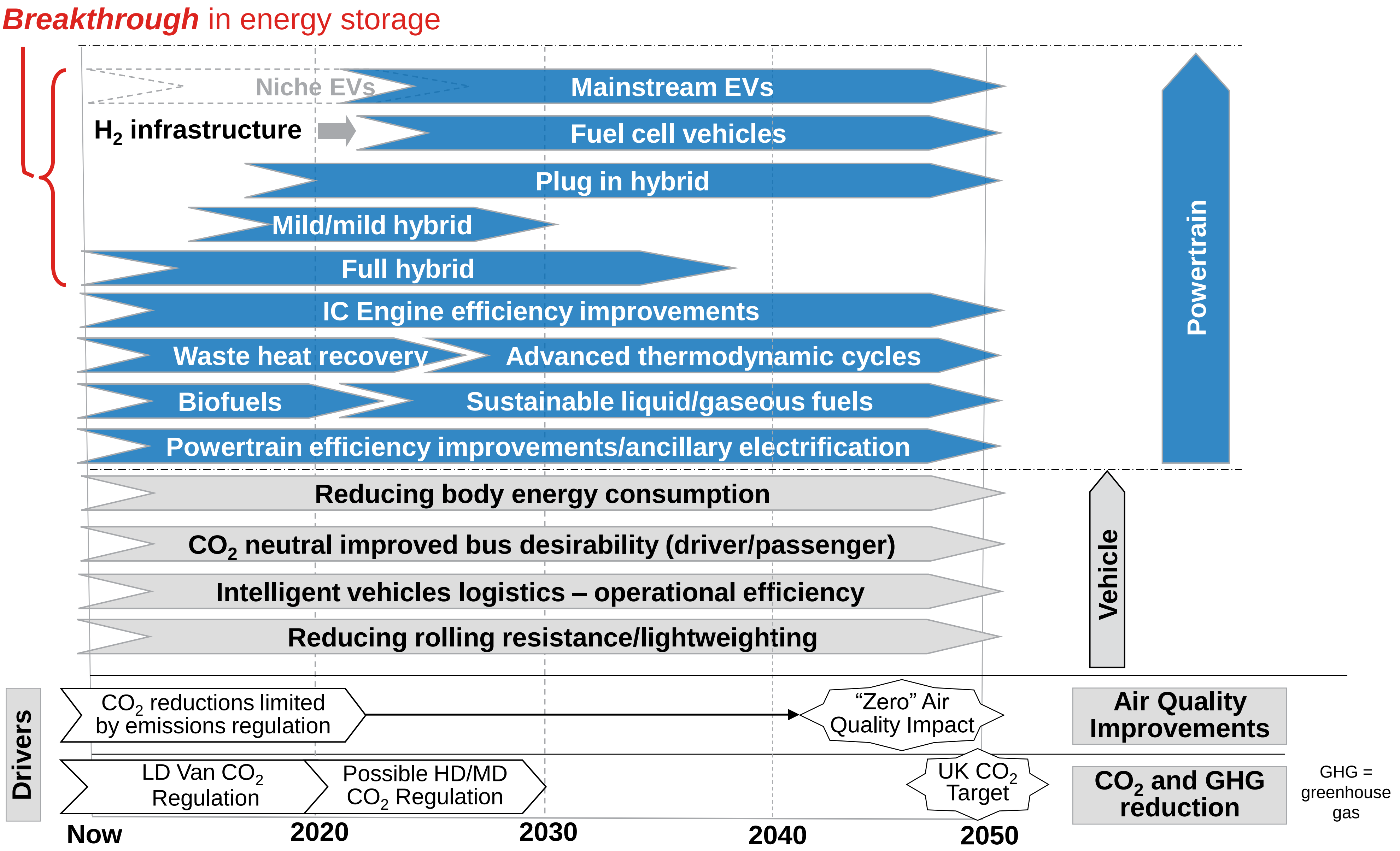
Contents

In the longer term there will be increasing national and international pressure to reduce Greenhouse Gas Emissions from transport

- In the UK, the climate change act (2008) set targets to reduce UK GHG emissions by 80% in 2050, relative to 1990 levels
  - The DECC Carbon Plan sets out the UK Government’s approach to meeting these targets
    - This plan suggests that ultra-low emissions technologies such as sustainable biofuels and electric, hydrogen or hybrid technologies will be needed to meet CO_2 targets
    - The continuation of the Green Bus fund is one of the key actions resulting from this Carbon Plan
- The 2011 EC White Paper ‘Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system’ sets an objective to reduce transport GHG emissions by 60% in 2050 compared to 1990 (as a contributor to reducing emissions from all sectors by 80-95%)
- The EC considers that a number of actions will be need to meet this target:
  - Improved vehicle efficiency through new engines, materials and design,
  - Cleaner energy use through new fuels and propulsion systems,
  - Better use of networks and more efficient fleet operation, with the support of information and communication systems.

Source: Climate Change Act 2008 (http://www.legislation.gov.uk/ukpga/2008/27/contents) DfT (http://www.dft.gov.uk/topics/sustainable/climate-change) , DECC Carbon Plan 2011 (http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf)

The development of advanced technologies for buses is needed, in parallel with improvements to ICEs, to meet long term CO_2 targets



Breakthrough in energy storage

Niche EVs

Mainstream EVs

H_2 infrastructure

Fuel cell vehicles

Plug in hybrid

Mild/mild hybrid

Full hybrid

IC Engine efficiency improvements

Waste heat recovery

Advanced thermodynamic cycles

Biofuels

Sustainable liquid/gaseous fuels

Powertrain efficiency improvements/ancillary electrification

Powertrain

Reducing body energy consumption

CO_2 neutral improved bus desirability (driver/passenger)

Intelligent vehicles logistics – operational efficiency

Reducing rolling resistance/lightweighting

Vehicle

Drivers

CO_2 reductions limited by emissions regulation

“Zero” Air Quality Impact

Air Quality Improvements

LD Van CO_2 Regulation

Possible HD/MD CO_2 Regulation

UK CO_2 Target

CO_2 and GHG reduction

GHG = greenhouse gas

Now

2020

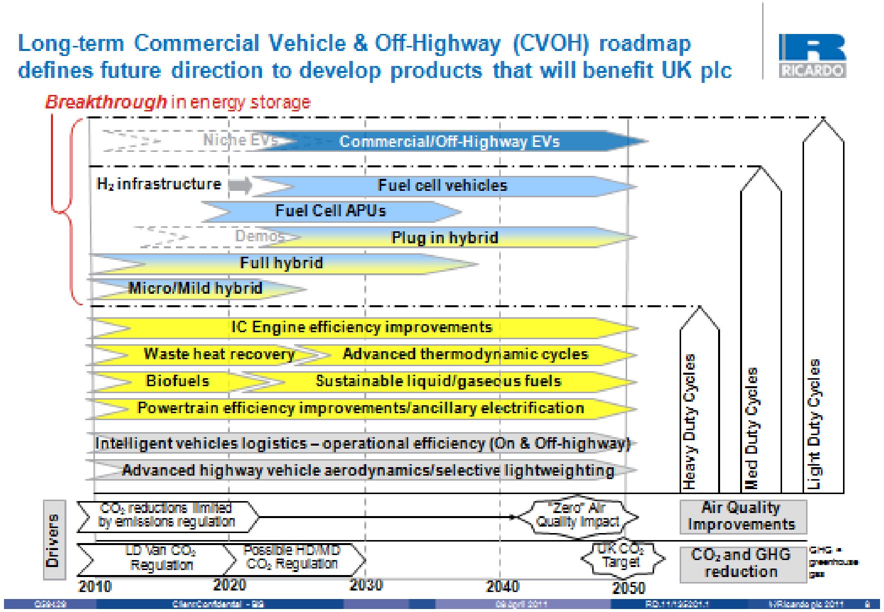
2030

2040

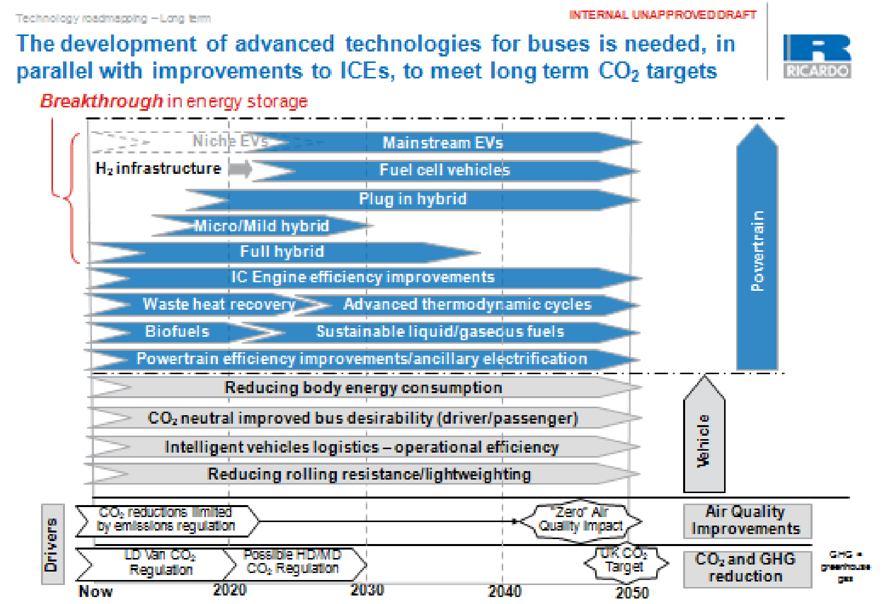
2050

The long term roadmap for urban buses has been developed from the Automotive Council Commercial Vehicle and Off Highway roadmap

- There are a many similarities between technology roadmaps for commercial vehicles and buses
- Key differences between commercial vehicle and bus roadmaps exist due to:
  - Bus urban duty cycle
  - Specific bus industry requirements – such as high body loads to open doors or kneel at bus stops
- The major benefits currently being sought for the commercial vehicle industry however are not likely to give the most significant CO_2 benefits for the bus industry
  - Therefore specific action may be required to pull through bus specific technologies



Long-term Commercial Vehicle & Off-Highway (CVOH) roadmap defines future direction to develop products that will benefit UK plc



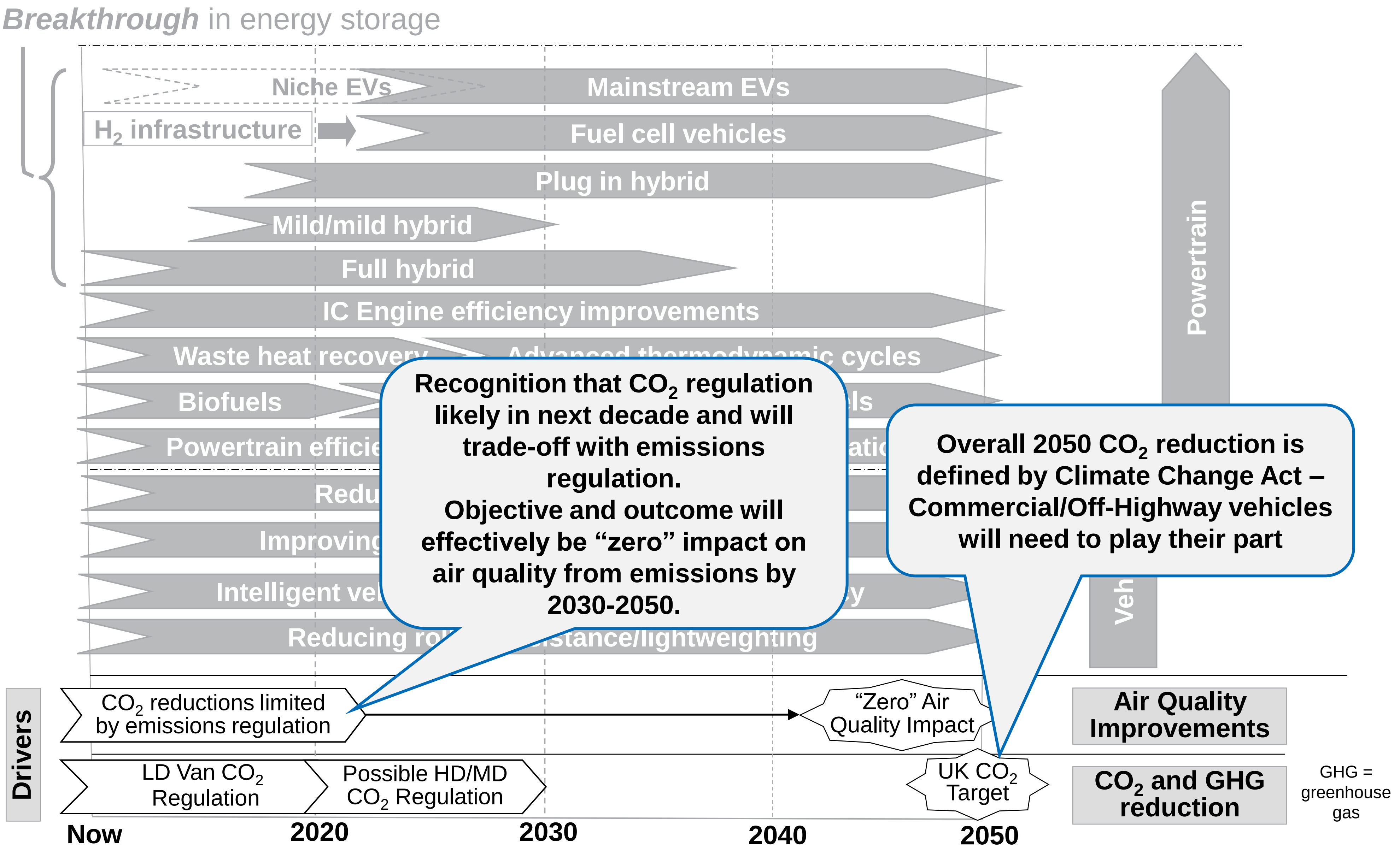
Technology roadmapping – Long term

INTERNAL UNAPPROVED DRAFT

The development of advanced technologies for buses is needed, in parallel with improvements to ICEs, to meet long term CO_2 targets

Source: Ricardo analysis, Automotive Council UK (http://www.automotivecouncil.co.uk/wp-content/uploads/2011/04/COM-OH-Roadmap-BIS.pdf)

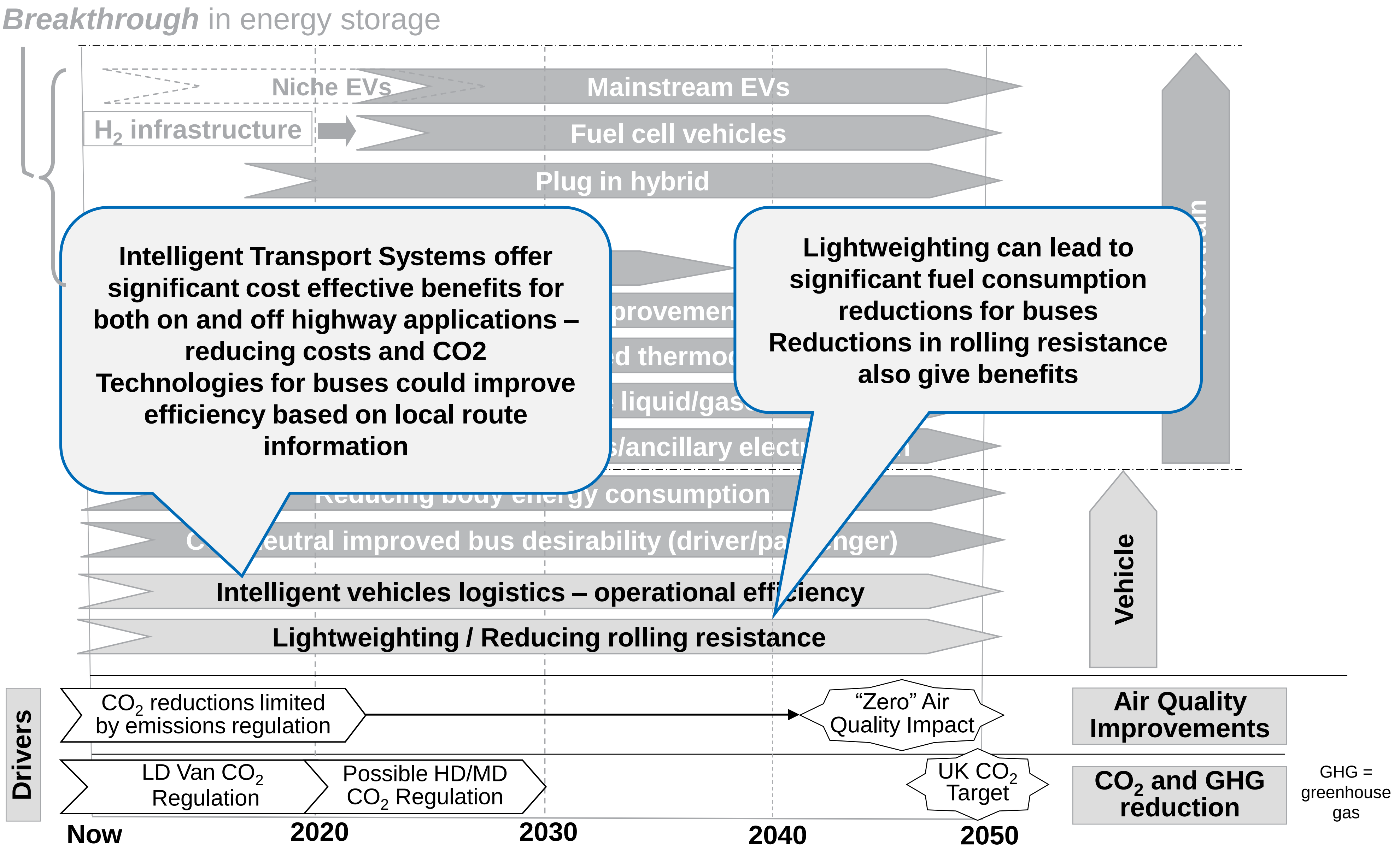
Long term targets for bus CO_2 reduction are defined by the 2008 Climate Change Act



Recognition that CO_2 regulation likely in next decade and will trade-off with emissions regulation.
Objective and outcome will effectively be "zero" impact on air quality from emissions by 2030-2050.

Overall 2050 CO_2 reduction is defined by Climate Change Act – Commercial/Off-Highway vehicles will need to play their part

ITS and lightweighting can both play a significant role in reducing bus energy consumption

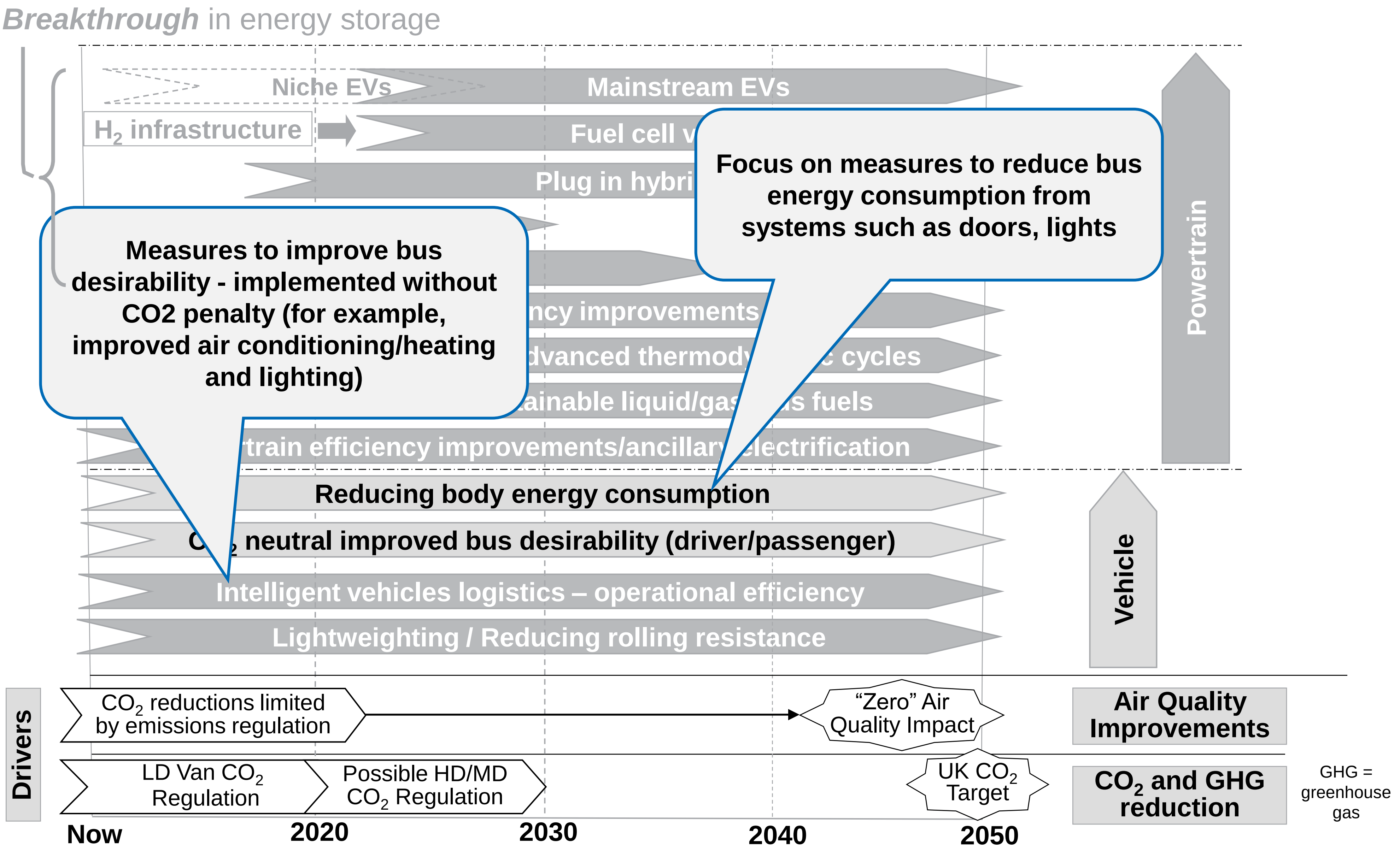


Breakthrough in energy storage

Intelligent Transport Systems offer significant cost effective benefits for both on and off highway applications – reducing costs and CO2
Technologies for buses could improve efficiency based on local route information

Lightweighting can lead to significant fuel consumption reductions for buses
Reductions in rolling resistance also give benefits

Measures to reduce body energy consumption and improve driver passenger comfort are key for the bus market



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Lightweighting / Reducing rolling resistance

Powertrain

Vehicle

Measures to improve bus desirability - implemented without CO2 penalty (for example, improved air conditioning/heating and lighting)

Focus on measures to reduce bus energy consumption from systems such as doors, lights

Drivers

CO_2 reductions limited by emissions regulation

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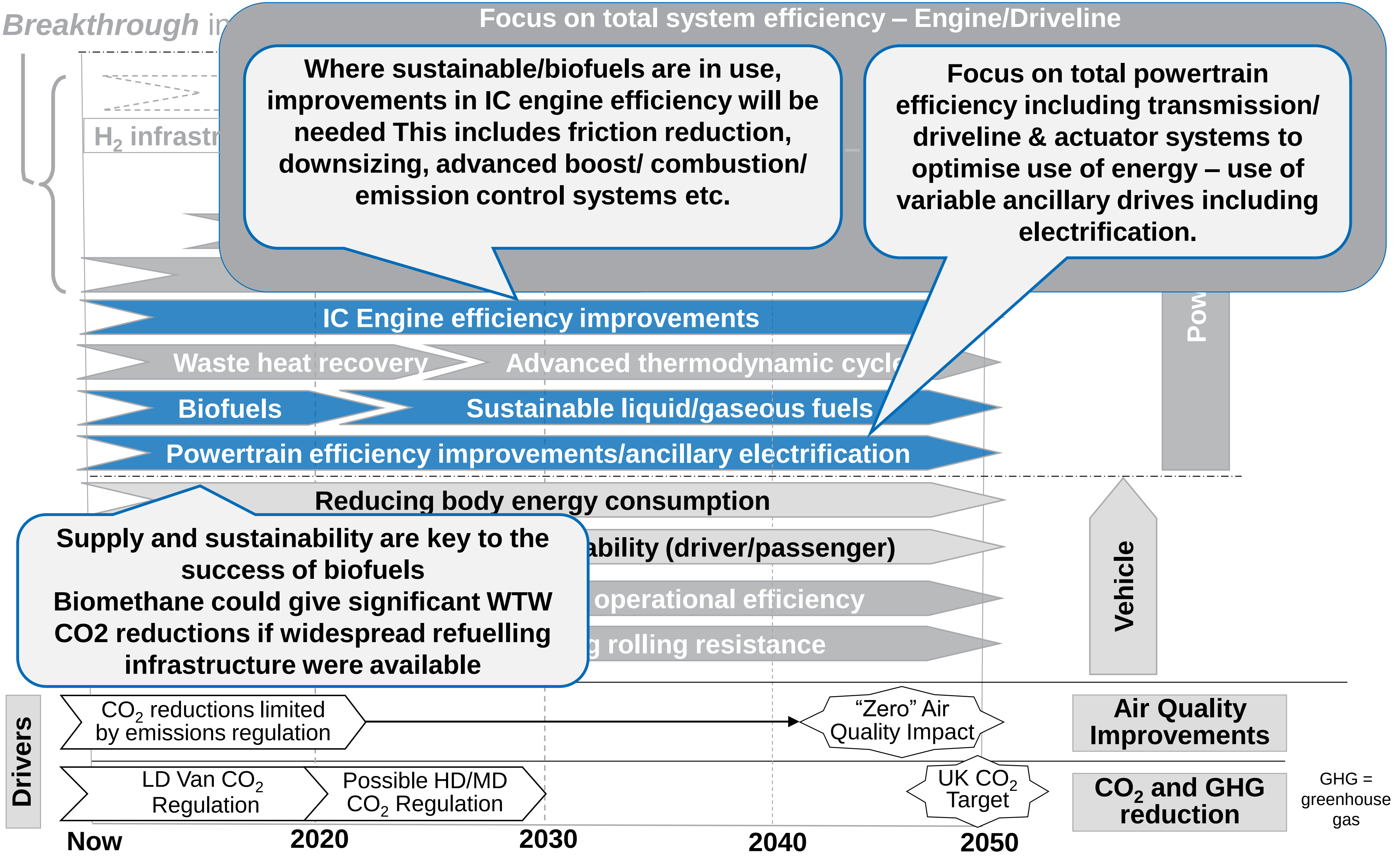
Now **2020** **2030** **2040** **2050**

Focus on improving total powertrain system efficiency will continue, using sustainable biofuels to give significant WTW benefits



Breakthrough i

H_2 infrastr

Focus on total system efficiency – Engine/Driveline

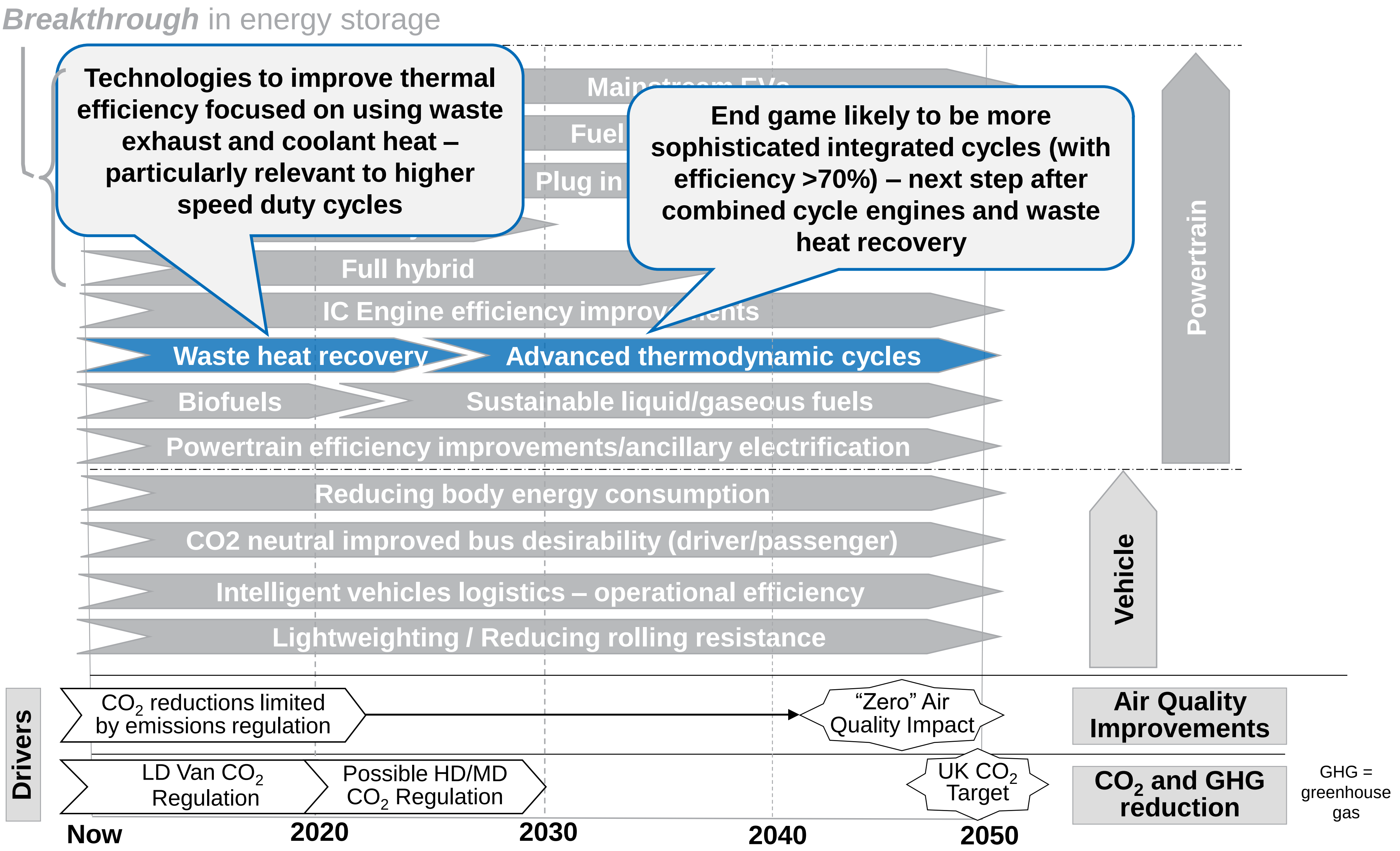
Where sustainable/biofuels are in use, improvements in IC engine efficiency will be needed This includes friction reduction, downsizing, advanced boost/ combustion/ emission control systems etc.

Focus on total powertrain efficiency including transmission/ driveline & actuator systems to optimise use of energy – use of variable ancillary drives including electrification.

Supply and sustainability are key to the success of biofuels
Biomethane could give significant WTW CO2 reductions if widespread refuelling infrastructure were available

GHG = greenhouse gas

Improved thermal efficiency through waste heat recovery and advanced thermodynamic cycles offer significant benefits



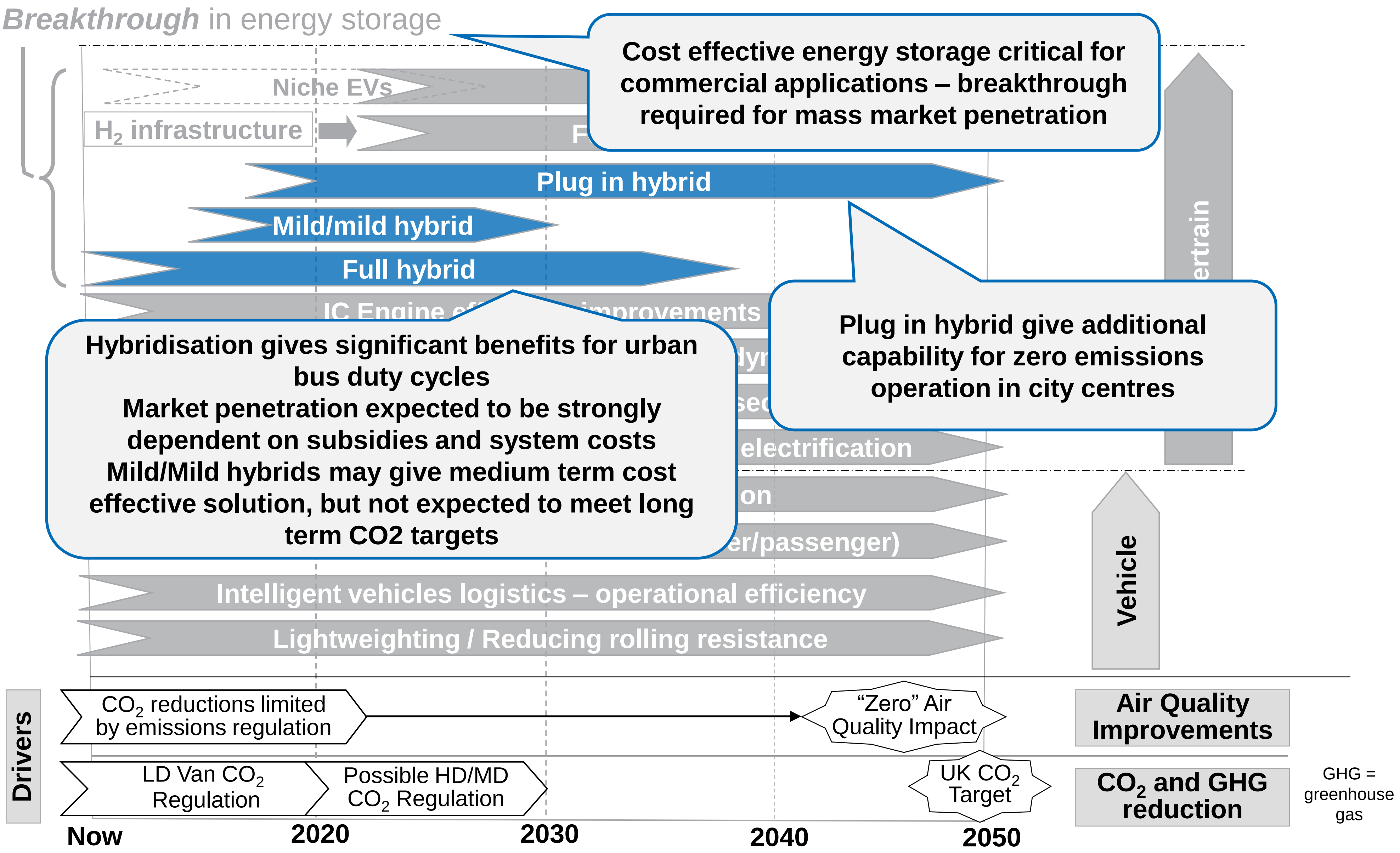
Breakthrough in energy storage

Technologies to improve thermal efficiency focused on using waste exhaust and coolant heat – particularly relevant to higher speed duty cycles

End game likely to be more sophisticated integrated cycles (with efficiency >70%) – next step after combined cycle engines and waste heat recovery

GHG = greenhouse gas

Hybridisation gives significant benefits for the urban bus duty cycle



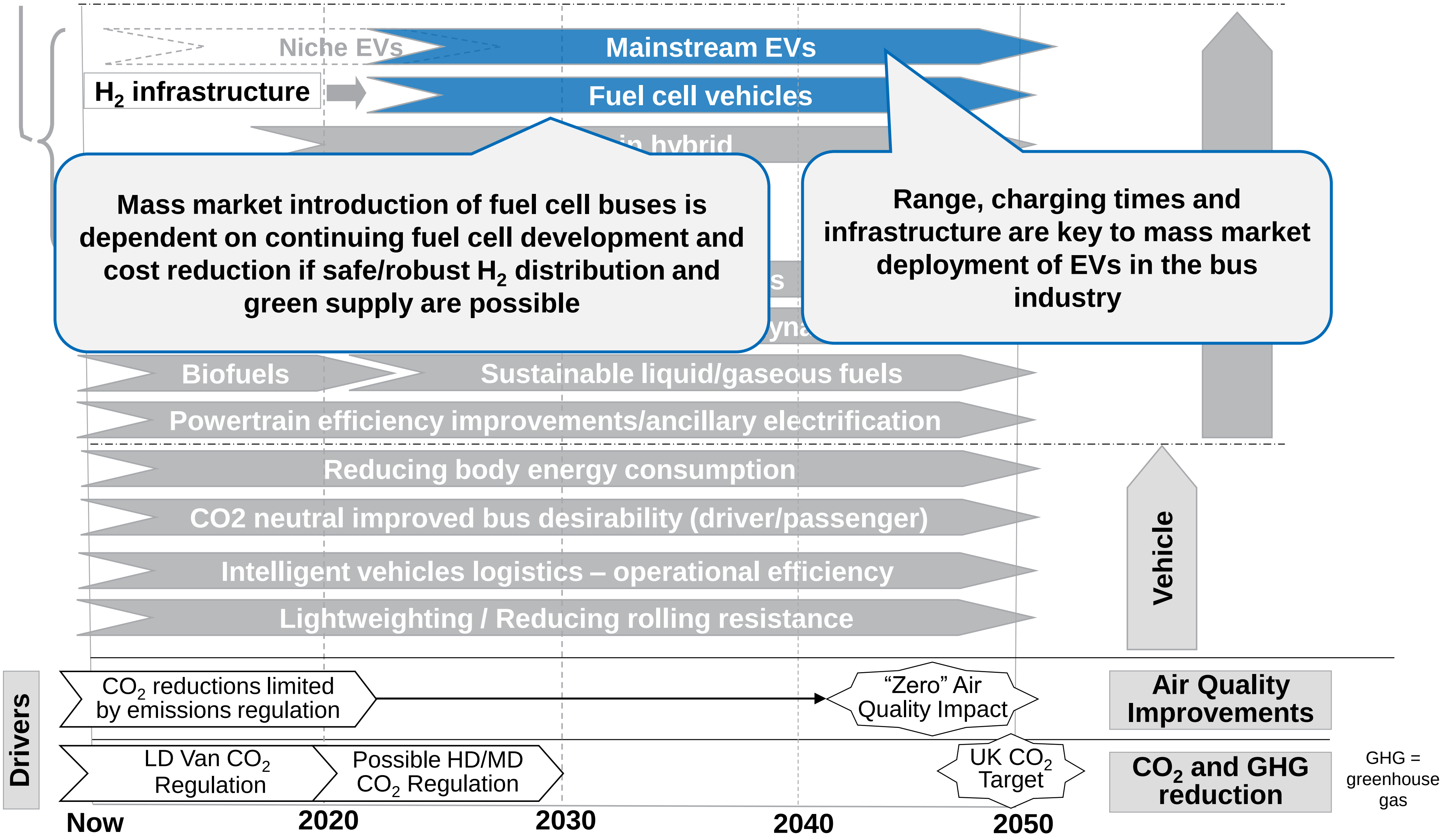
Cost effective energy storage critical for commercial applications – breakthrough required for mass market penetration

Plug in hybrid give additional capability for zero emissions operation in city centres

Hybridisation gives significant benefits for urban bus duty cycles
Market penetration expected to be strongly dependent on subsidies and system costs
Mild/Mild hybrids may give medium term cost effective solution, but not expected to meet long term CO2 targets

Fuel cell and battery electric vehicles both give potential for zero emissions at point of use

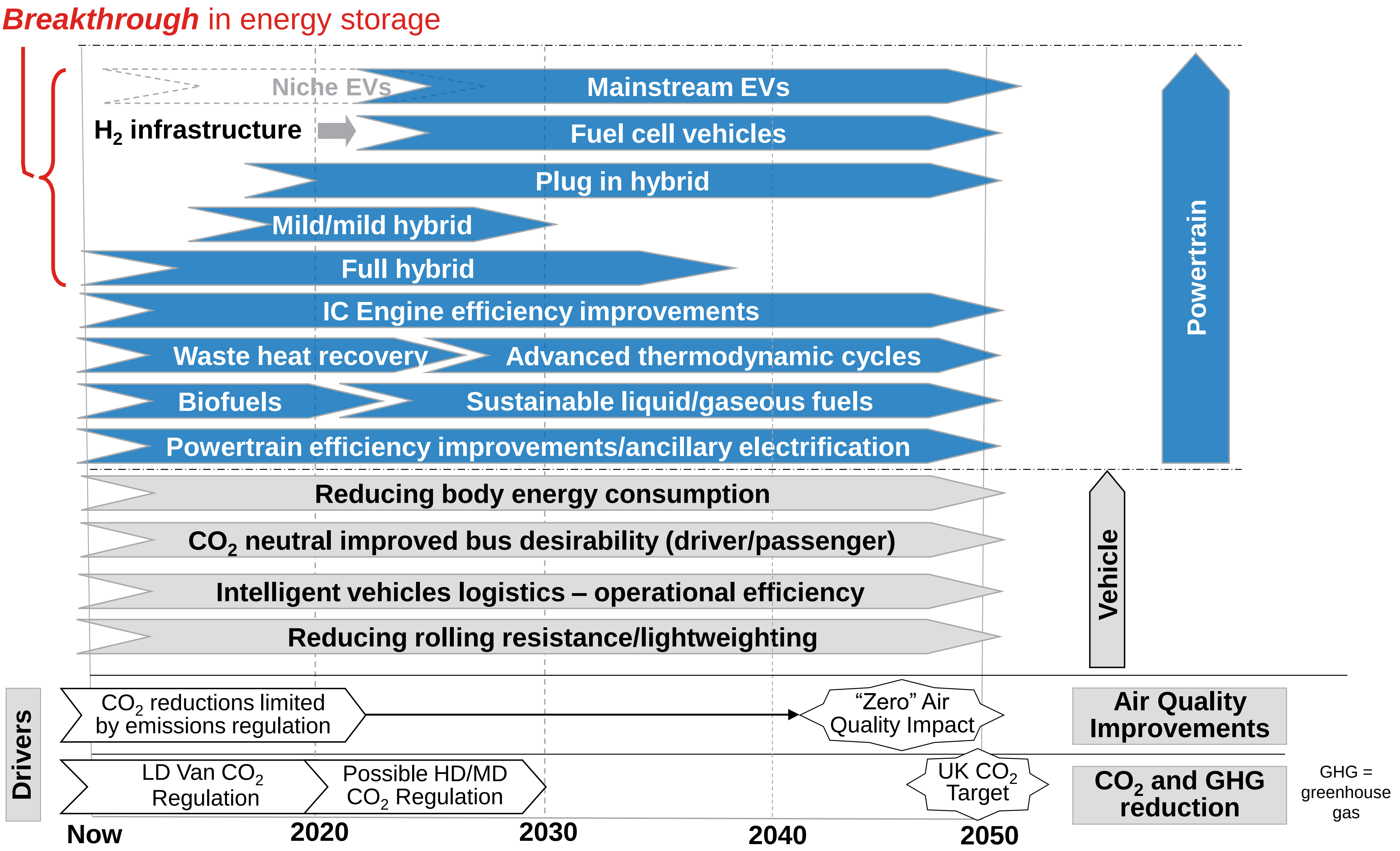
Breakthrough in energy storage



Mass market introduction of fuel cell buses is dependent on continuing fuel cell development and cost reduction if safe/robust H_2 distribution and green supply are possible

Range, charging times and infrastructure are key to mass market deployment of EVs in the bus industry

The long term bus CO_2 reduction roadmap



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Conclusions (1/2)

- Technologies were selected for inclusion in this study where they were expected to give > 2% CO_2 benefit for UK single and double deck urban buses, selected technologies are shown below:
  - Vehicle and powertrain technologies: Lightweighting, smart clutched compressor, smart alternator, Rankine cycle, IVT, stop start, mild hybrid, series and parallel electric and hydraulic hybrids
  - Fuels: Compressed natural gas (CNG or LNG), compressed biomethane, HVO, BTL, Hydrogen (Internal combustion engines and fuel cell), electricity
- Analysis of WTW CO_2 emissions for each technology was carried out
  - Biomethane is expected to give significant WTW CO_2 reductions for bus application, however expected UK pathways do not match those examined in the literature
  - WTW CO_2 benefits for fossil CNG technologies vary from an increase compared to Diesel to a significant benefit depending on engine technology and gas pathway
  - Detailed independent analysis of the WTT CO_2 emissions for UK developing biomethane and fossil CNG pathways is recommended
- Payback time was estimated for these technologies for single and double deck vehicles, both with and without UK bus subsidies
  - Under the current subsidy regime, hybrid and biomethane powered vehicles are expected to have a payback time less than 5 years
    - If no fuel or capital subsidies were available, payback times for most hybrid and gas powered technologies are likely to be greater than 5 years
  - Technologies that were expected to have a payback time of less than 5 years without support were mild hybrid, flywheel hybrid, IVT, hydraulic series hybrid, PBS and smart ancillaries

Conclusions (2/2)

- Technology packages were then generated to give a range of benefits for UK buses
  - Selected packages were: stop start with smart ancillaries; mild hybrid with smart ancillaries; flywheel hybrid with stop start; full series hybrid with biomethane fuelled engine
- The suitability of the selected technologies for other commercial vehicle sectors was examined to identify areas where economies of scale or other synergies may be achieved
  - Lightweighting, smart ancillaries, full hybrid, flywheel hybrid, pneumatic booster, biomethane/CNG and substitutional biofuels are expected to be applicable across a range of commercial vehicle sectors
- The major benefits currently being sought for the commercial vehicle industry however are not likely to give the most significant CO_2 benefits for the bus industry
    - Therefore specific action may be required to pull through bus specific technologies
- Roadmaps were then developed for UK buses for both the long and short term (up to 2020)
  - Short term roadmapping showed that many low carbon technologies require development for bus application
    - In the near term, while many biofuel and alternative fuel options exist for buses, only CNG or biomethane have the potential for mass market penetration
  - In the longer term, the development of advanced technologies for buses is needed, in parallel with improvements to ICEs, to meet long term CO_2 targets

Appendix 1 – MLTB cycle statistics

MLTB cycle statistics were used in the assessment of CO_2 reduction potential for relevant technologies

Attribute	MLTB cycle
Distance (km/[mi])	9/[5.6]
Time (min)	38
# cycles/time for typ 120mi daily mileage[1]	~22/14hr
Max speed (km/h)	49
Ave speed (km/h)	14
Ave/max ratio (%)	29%
Max accel (m/s2)	1.5
Ave accel (m/s2)	0.5
Idle time %[2]	40%
Average positive power (kW)[3]	54kW
Maximum positive power (kW)	155kW
Stationary time %	36%
Cruise time %[4]	34%
Longest cruise duration (s)	5 sec
Acc time %	25%
Dec time %	5%

Notes: 1: assuming 40000mi/yr, 50wks/yr. 2 based on cycle power between 0 & 24kW 3: based on 19t DD 4: based on acc ~=0, i.e. Between -0.1 & +0.1m/s2