Review of Low Carbon Technologies for Heavy Goods Vehicles

Prepared for Department for Transport

RD.09/182601.6

June 2009

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Executive Summary

- Emissions from freight movements stem primarily from the road sector – HGVs represent 24% and vans 12% of total domestic transport greenhouse gases[1)]
- DfT therefore need to consider what type of framework, regulatory, funding to support investment or best practice programmes, will help us effectively incentivise the uptake of lower carbon technologies particularly for HGVs
- But before considering any framework for HGVs, the range of low carbon technologies and their applicability to HGVs needs to be understood
- The project uses a three step approach to identify, analyse and summarise applicability of low carbon technologies for HGVs
- The low carbon technologies reviewed for application to HGVs are grouped into vehicle, powertrain and fuel themes
  - For the vehicle theme, technologies lie in the fields of improving aerodynamics, reducing rolling resistance and driver behaviour
  - For the powertrain theme, 4 main areas of low carbon technologies are identified; engine efficiency, waste heat recovery, alternative powertrains and transmissions
  - For the fuel theme, 3 alternative fuels have been identified for analysis, along with three different methods of producing biodiesel
- The feasibility analysis was conducted using two different vehicle benchmarks, medium and heavy duty, to allow for the differences in typical vehicle operation and hence potential CO_2 benefit of a technology
- Results of the analysis show that:
  - Aerodynamic trailers, electric bodies & vehicle platooning may have the greatest CO_2 reduction potential for vehicle technologies
  - Powertrain technologies which may offer greatest tailpipe CO_2 reduction are electric drives, fuel cells and full hybrids but benefits are application specific, with significant lifecycle CO_2 impacts dependent on energy mix
  - Fuel technologies with greatest lifecycle CO_2 benefits may be biogas, biofuels and hydrogen, however tailpipe CO_2 reductions are lower

Source: 1) National Atmospheric Emissions Inventory (NAEI), available at http://www.naei.org.uk/emissions

Executive Summary

- 7 of the technologies reviewed have been identified as potential indicative guides for CO_2 benefit due to their limited fields of application and narrow benefit ranges associated with it
- An indicative guide means, if a particular technology is applied to a particular vehicle type, the CO_2 benefits are consistent, repeatable and not significantly affected by variables such as vehicle load and driving style, such that statistics about take-up of a particular technology can be translated into an estimated fleet CO_2 saving
  - Example:
    - Aerodynamic trailers are a good indicative guide, their CO_2 saving performance is consistent and repeatable when applied to heavy duty articulated vehicles used on a constant high speed duty cycle
    - Full hybrids are a poor indicative guide, as their CO_2 improvement benefit is highly dependent on duty cycle, vehicle architecture, battery size, and environmental impact is strongly dependent on battery technology
- Even the technologies deemed as “good” indicative guides only act as good indicators when applied to specific vehicle applications and duty cycles. Very few technologies can be viewed as “blanket” indicative measures regardless of vehicle implementation

Contents

A to GC

- ACC – Adaptive Cruise Control
- AMT – Automated Manual Transmission
- APU – Auxiliary Power Unit
- A/T – Aftertreatment
- BSFC – Brake Specific Fuel Consumption
- BTL – Biomass to Liquid
- CAA – Clean Air Act
- CBG – Compressed Bio-Gas
- CFD – Computational Fluid Dynamics
- CNG – Compressed Natural Gas
- CO – Carbon Monoxide
- CO_2 – Carbon Dioxide
- DCT – Dual Clutch Transmission
- DEER – Diesel Engine Emissions Reduction
- Defra – Department for Environment, Food and Rural Affairs
- DfT – Department for Transport
- DI-CR – Direct Injection Common Rail
- DI-UI – Direct Injection Unit Injectors
- DME – Di-Methyl Ester
- DOHC – Double Overhead Camshaft
- DPF – Diesel Particulate Filter
- EAD – Enhanced Acceleration Deceleration
- ECA – Enhanced Capital Allowance
- ECT – Emissions Control Technology
- EDC – Electronic Diesel Control
- EEV – Enhanced Environmental Vehicle (pull forward Euro 5)
- EGR – Exhaust Gas Recirculation
- EMS – Engine Management System
- EPA – Environmental Protection Agency
- EPAS – Electric Power Assisted Steering
- ESC – Electronic Stability Control
- EST – Energy Savings Trust
- ETC – European Transient Cycle
- ETBE – Ethyl Tertiary Butyl Ester
- EtOH – Ethanol
- EU – European Union
- EV - Evaporator
- FAME – Fatty Acid Methyl Ester
- FBP – Freight Best Practice
- FC – Fuel Cell
- FEAD – Front End Accessory Drive
- FIE – Fuel Injection Equipment
- FTP – Federal Test Procedure
- GCW – Gross Combined Weight

GH to RG

- GHG – Greenhouse Gas
- GPS – Global Positioning System
- GRP – Glass Reinforced Plastic
- GTL – Gas to Liquid
- GVW – Gross Vehicle Weight
- HCCI – Homogenous Charge Compression Ignition
- HDV – Heavy Duty Vehicle
- HDDE – Heavy Duty Diesel Engine
- HE – Heat Exchanger
- HGV – Heavy Goods Vehicle
- HPL – High Pressure EGR Loop
- HV – High Voltage
- HVO – Hydrogenated Vegetable Oil
- ICE – Internal Combustion Engine
- IFP – Institute Français de Pétrole
- L4 – Inline 4 Cylinder Engine
- LBM – Liquid Bio-Methane
- LCV/LDV – Light Commercial/Duty Vehicle
- LDW – Lane Departure Warning
- LNT – Lean NOx Trap
- LPG – Liquid Petroleum Gas
- MDV – Medium Duty Vehicle
- MoS_2 – Molybdenum Disulphide
- MOT – Ministry of Transport Test (Vehicle Road Worthiness)
- MPG – miles per gallon
- MTBE – Methyl Tertiary Butyl Ester
- MtOH – Methanol
- NA – Naturally Aspirated
- NAFTA – North American free Trade Association
- NCS – Nitrogen Conditioning System
- NEDC – New European Drive Cycle
- NG – Natural Gas
- NOx – Oxides of Nitrogen
- OEM – Original Equipment Manufacturer
- PBS – Pneumatic Booster System
- PEM – Polymer Electrolyte Membrane
- PM – Particulate Matter
- Pmax – Maximum cylinder pressure
- POC – Partial Oxidation Catalyst
- PSI – pounds per square inch
- PVD – Physical Vapour Deposition
- Ra – Surface Roughness
- RC – Recuperator
- R&D – Research and Development

RH to Z

- RHA – Road Haulage Association
- RPM – Revolutions Per Minute
- RTFO – renewable Transport Fuels Obligation
- SAE – Society of Automotive Engineers
- SAFED – Safe and Fuel Efficient Driving
- SCR – Selective Catalytic Reduction
- SH – Super Heater
- SMR – Steam Methane Reforming
- SOFC – Solid Oxide Fuel Cell
- SOP – Start of Production
- SOx – Sulphur Oxides
- SUV – Sports Utility Vehicle
- TC – Turbocharger
- TCI – Turbocharged, Intercooled
- TE – Thermoelectric
- TPCS – Tyre Pressure Control System
- TRL – Transport Research Laboratory
- UDDC – Urban Driving Duty Cycle
- VAT – Value Added Tax
- VDA – Verband der Automobile
- VED – Vehicle Excise Duty
- VFP – Variable Flow Pump
- VGT – Variable Geometry Turbocharger
- VVT – Variable Valvetrain
- WTW – Well to Wheels

Contents

This section provides clarification of some of the terminology used in the review that may be unfamiliar to the reader

- This section aims to provide additional information to aid understanding on some of the more complex and less self explanatory low carbon technologies reviewed
- The following classifications of light and heavy goods vehicles have been used within this report (unless where otherwise stated):
  - LCV / LDV – light commercial / duty vehicle, any vehicle up to and including 3.5t GVW
  - HGV – Heavy Goods Vehicle, goods transport vehicles with >3.5t GVW
- For the purpose of this review to better understand the applicability of low carbon technologies to heavy goods vehicles, the HGV segment has been further segmented as follows:
  - MDV – medium duty vehicle, 3.5 – 15t GVW, including both rigid and drawbar trailer vehicles
  - HDV – heavy duty vehicle, >15t GVW, including both rigid and articulated vehicles
- The vehicle were segmented as above to provide two separate duty cycles against which the low carbon technologies could be evaluated and are:
  - Medium Duty - Urban cycle, vehicles in this segment tend to be used as delivery vehicles with majority urban driving and frequent stop / start activity
  - Heavy Duty – Motorway cycle, vehicles in this segment tend to do long haul distribution with majority continuous high speed driving with infrequent stop /start activity

Fuel consumption differs from fuel economy and is directly related to CO_2 emissions for a given fuel

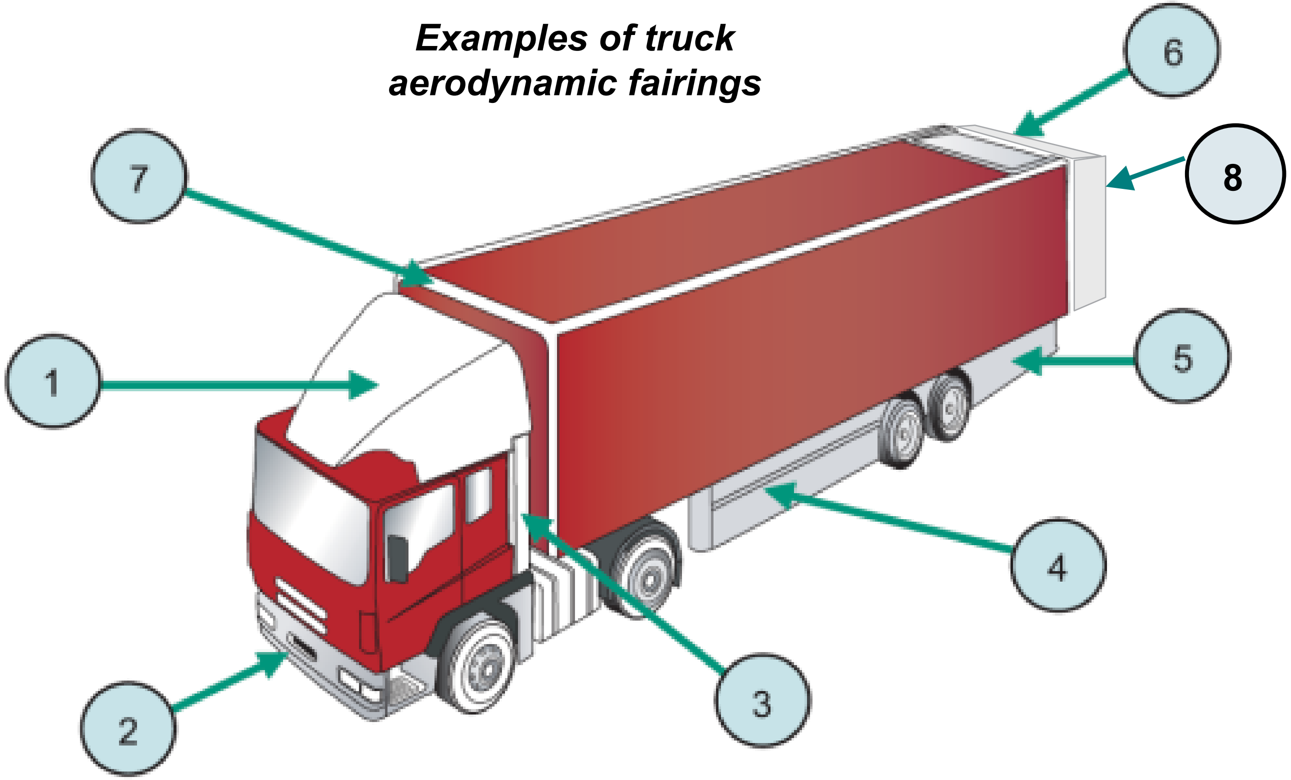
- CO_2 (carbon dioxide) – the most common greenhouse gas, although it does not have the highest global warming potential on a mass basis
- Fuel consumption – the amount of fuel consumed to perform a particular task. Typical units include:
  - Litres per 100km (l/100km)
- Brake specific fuel consumption (BSFC) – the amount of fuel consumed to produce a unit of engine power (at the crankshaft). Typical units:
  - Grams per kW-hour (i.e. g/h ÷ kW) – g/kWh
- For both fuel consumption and BSFC, a lower number is better
- Fuel economy – the amount of useful work done for a given amount of fuel. Typical units are:
  - Miles per gallon (mpg)
- For fuel economy a higher number is better
- Fuel consumption and CO_2 emissions are directly correlated for a given fuel – e.g. diesel or gasoline. Fuels with different carbon content (i.e. chemically different composition) have different correlation gradients. Fuel economy and CO_2 are inversely related.
- Tailpipe CO_2 (usually g/km) refers to CO_2 emissions directly from the vehicle as a result of combustion of fuel
- Lifecycle CO_2 (quoted in a variety of units) refers to the well-to-wheel CO_2 emissions of a particular activity, and captures the CO_2 emitted during fuel production, distribution and combustion

Aerodynamic fairings covers a range of add on devices including cab deflectors, side skirts, cab collars and trailer fairings

Aerodynamic Fairings

- Additional add-on to trailers and cabs that help reduce aerodynamics drag and improve fuel consumption
- Technologies include, cab deflectors, trailer side skirts, cab collars, all aimed at reducing aerodynamic drag and can be added as aftermarket additions

① Cab Deflector / Fairing
② Air Dam
③ Cab Collar
④ Side Skirt
⑤ Rear Quarter Panel
⑥ Tapered Roof
⑦ Trailer Front Fairing
⑧ Boat-tail plates/extenders



Examples of truck aerodynamic fairings

Source: Freight Best Practice, Smoothing the Flow at TNT Express and Somerfield using Truck Aerodynamic Styling, June 2006

Hybrid and electric vehicles covered by this review include stop / start, full and plug-in hybrids along with full electric vehicles

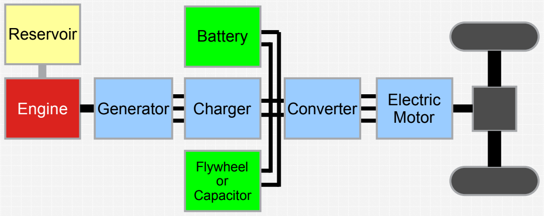
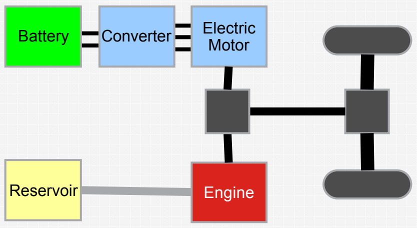
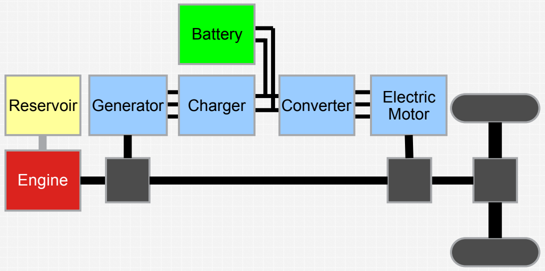
Hybrid and Electric Vehicle Overview

	Stop-Start	Mild Hybrid	Full Hybrid	Plug-in Hybrid	Electric
Description	● Uprated starter motor / belt starter generator + uprated battery. Shuts off engine when vehicle stationary, restarts on pullaway	● Small motor that supplements engine power, usually used together with a down-sized engine	● 1 or 2 electric motors of significant power ● Wheels can be driven either by the IC engine or the electric motor	● Combination of electric vehicle with a small IC engine as a range extender. Vehicle is plugged in to charge	● Vehicle driven by an electric motor, where energy is from a battery, which requires plugging in to charge
Benefits	✓ Low cost ✓ Minimal change from baseline ✓ Good FC benefit in heavy urban traffic	✓ Enables engine downsizing ✓ Improved refinement & performance ✓ Increased generating power	✓ Enables downsized enigne and better performance ✓ Best balance in FC and emissions savings ✓ Electric only mode possible	✓ Allows further engine downsizing resulting in lower CO_2	✓ Zero emission vehicle (ZEV) at tailpipe ✓ Low noise
Limits	× No downsizing possibility × No improvement of performance × Limited FC benefit in highway operation	× Expensive × No electric only mode × Space / cooling for electronics & batteries	× Very expensive × Increased transmission losses from series-parallel × Ltd trailer tow ability	× Expensive due to battery requirements × Vehicle charging infrastructure required	× Expensive battery requirements × Vehicle charging infrastructure × CO_2 emissions depend on energy source
Current Applications	● Urban delivery vans, gasoline/diesel cars	● Urban delivery vans, gasoline cars	● Cost-effective gasoline or diesel family vehicles with mixed usage & CVs	● No vehicles yet in the market	● Niche city cars and urban delivery vehicles, currently limited up to 12t

Source: Ricardo Analysis

Of the three main system layouts all can be used for commercial vehicles applications, with HGVs favouring parallel systems

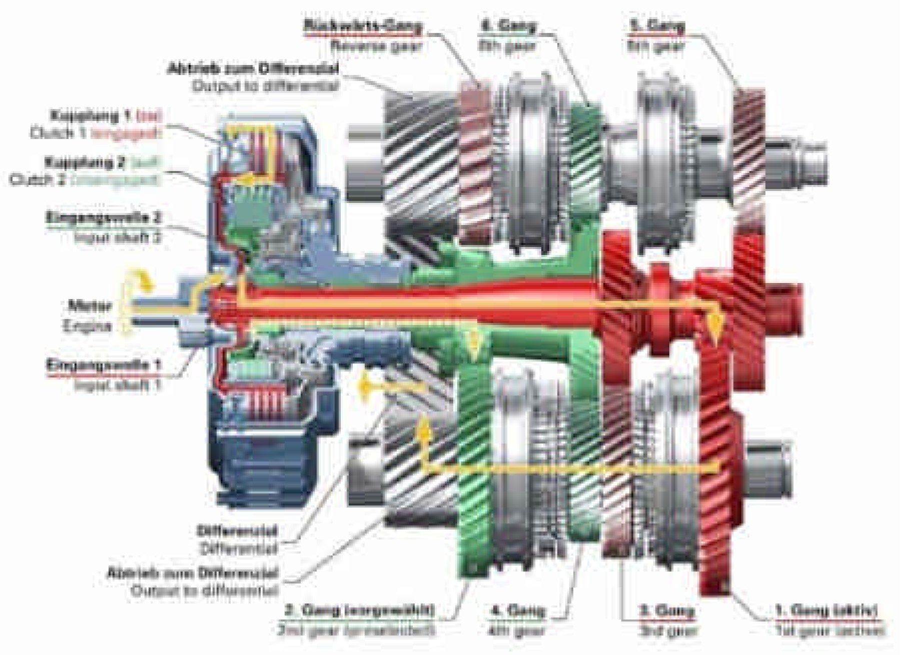
Hybrid Layouts

	Series Hybrid	Parallel Hybrid	Series - Parallel
Description	- In a series hybrid system, the combustion engine drives an electric generator instead of directly driving the wheels - The generator both charges a battery and powers an electric motor that moves the vehicle - When large amounts of power are required, the motor draws electricity from both the batteries and the generator	- Parallel hybrid systems have both an internal combustion engine (ICE) and an electric motor, connected to a mechanical transmission - Most use an electrical motor / generator located between the ICE and transmission, replacing the starter motor and alternator - An additional high voltage battery is required to power accessories (HVAC, Power Steering) rather than the ICE	- Combined hybrid systems have features of both series and parallel hybrids - They incorporate power-split devices allowing for power paths from the engine to the wheels that can be either mechanical or electrical - The main principle behind this system is the decoupling of the power supplied by the engine (or other primary source) from the power demanded by the driver
Schematics & Examples	 - Used for commercial vehicles, most often for buses	 - Used for passenger car hybrids and on commercial vehicles	 - Used for gasoline hybrid passenger cars and commercial vehicles

Source: Ricardo

AMT and DCT transmissions are single and dual clutch automated layshaft transmissions

- Automated manual transmissions (AMT) combine the best features of manual and automatic transmissions
- Based on a manual transmission an AMT operates similarly except that it does not require clutch actuation or shifting by the driver. This is done automatically, controlled electronically (shift-by-wire) and performed by a hydraulic system or electric motor
- Dual clutch transmissions are also based on layshaft transmissions like a manual, but have twin clutches and twin input shafts – see cutaway
- The system works like this:
  - One clutch controls gears 1, 3, 5, and 7 while the other deals with 2, 4, and 6
  - If the driver shifts up to 3rd, the unit then preselects 4, with that clutch open. When the driver then selects 4th, the even-number clutch closes and simultaneously the odd clutch opens
  - The handover between clutches means that there is never torque interrupt as in a manual or AMT, so drive torque is continued and shift comfort is increased



Audi DSG Dual Clutch Transmission Cutaway

Source: www.fueleconomy.gov; www.autobloggreen.com

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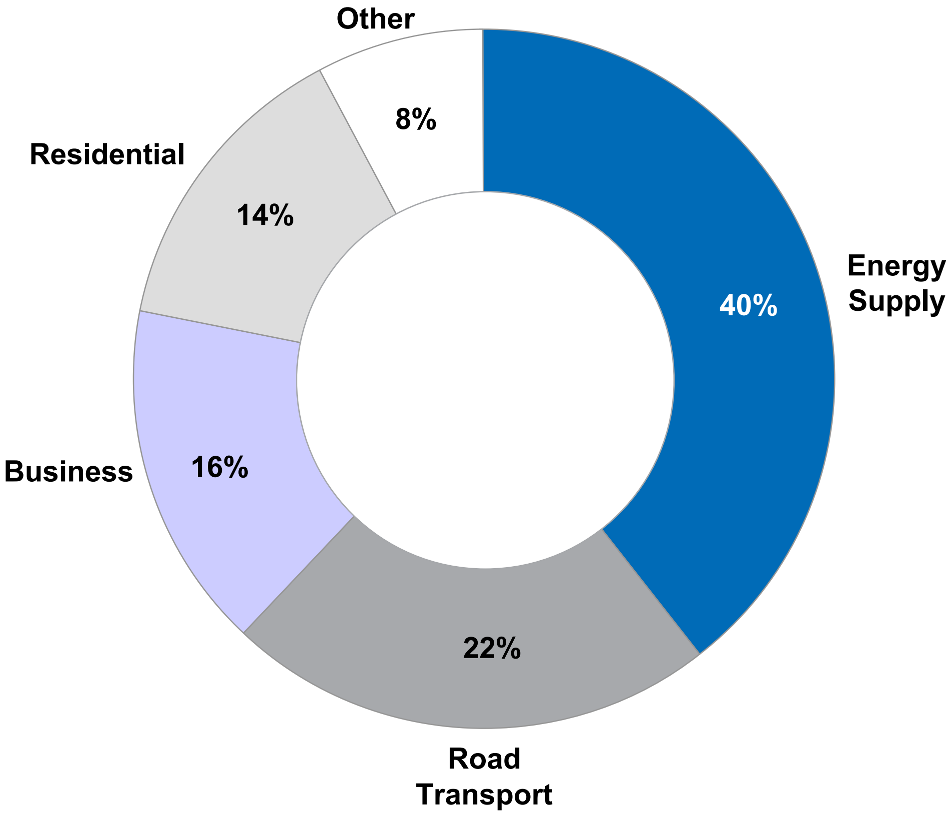
Road Transport accounted for 22% of all UK CO_2 emissions in 2007 and unlike other industries, levels have been increasing since 1990

UK CO_2 Emissions by source, 2007



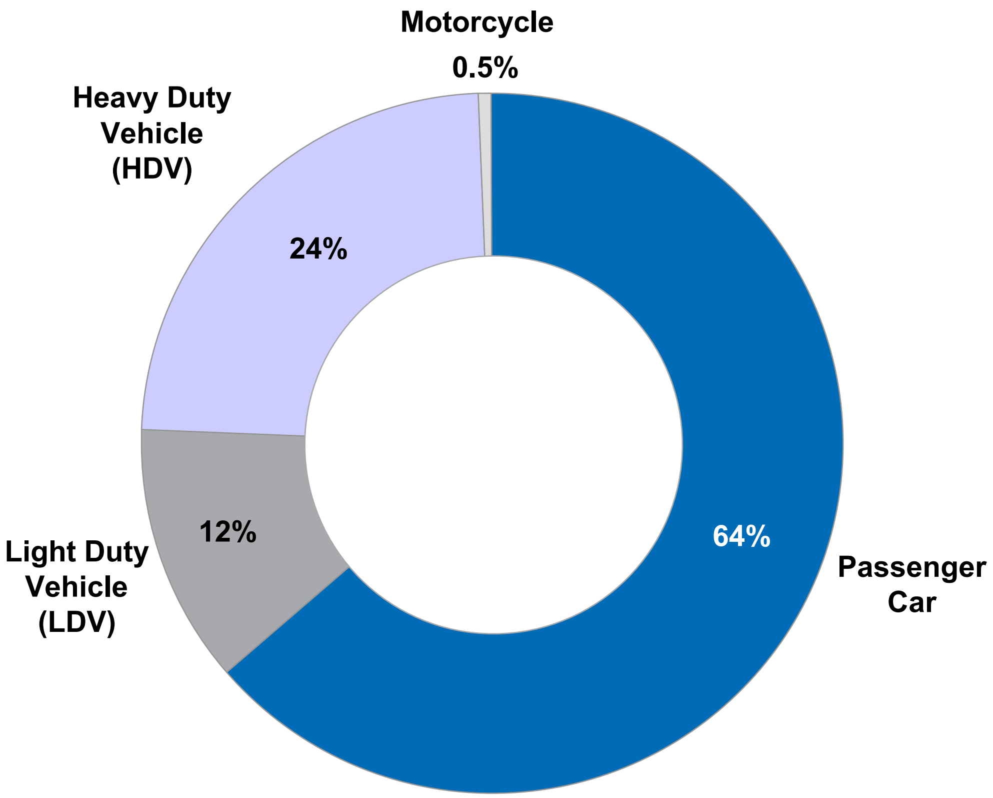
Key Insights

- Carbon dioxide is the main man-made contributor to global warming and accounted or 85% of UK man-made greenhouse gas emissions in 2007
- Using data provided by Defra, the breakdown of CO_2 emissions in 2007 was as follows:
  - 40% from the energy supply sector
  - 22% from road transport
  - 16% from business
  - 14% from residential use
- Since 1990, CO_2 emissions from road transport have increased by 11%, while they have reduced from the energy supply industry by 12% and business emissions by 19%
- Even compared to 2006, emissions from road transport have risen by 1%, whilst emissions from energy supply, business and residential fossil fuel use have fallen by 2, 3 and 5% respectively

Source: Defra website at: www.defra.gov.uk/environment/statistics/globatmos/.

While passenger cars account for the majority of Road Transport CO_2 emissions, HDVs still have a significant and increasing contribution

UK Road Transport CO_2 Emissions by type, 2007



Key Insights

- Data supplied by the National Atmospheric Emissions Inventory for 2007 shows the breakdown of the 22% contribution of road transport to CO_2 emissions
  - –The majority, 64% is from passenger cars
  - –12% is from Light Duty Vehicles (LDVs)
  - –24% is from Heavy Duty Vehicles (HDVs)
  - –0.5% is from motorcycles and mopeds
- HDV CO_2 emissions have increased by 10% from 1990, second only to LDVs which increased by 40%, with passenger cars increasing by 7.4% and motorcycles emissions reducing by 6.5%
- While LDV and passenger car volumes have increased by 37% and 34% respectively, HDV volumes have dropped by 9.4%
- Compared to 2006 HDV emissions increased by 3.5%, LDV by 3.2% and motorcycles by 9.3%. Only passenger cars emissions reduced and this was only by a small margin, 0.4%

Source: National Atmospheric Emissions Inventory (NAEI), available at http://www.naei.org.uk/emissions

Mandatory CO_2 targets for passenger cars have already been introduced by the EU…

Europe: CO_2 legislation

Key features of the resolution

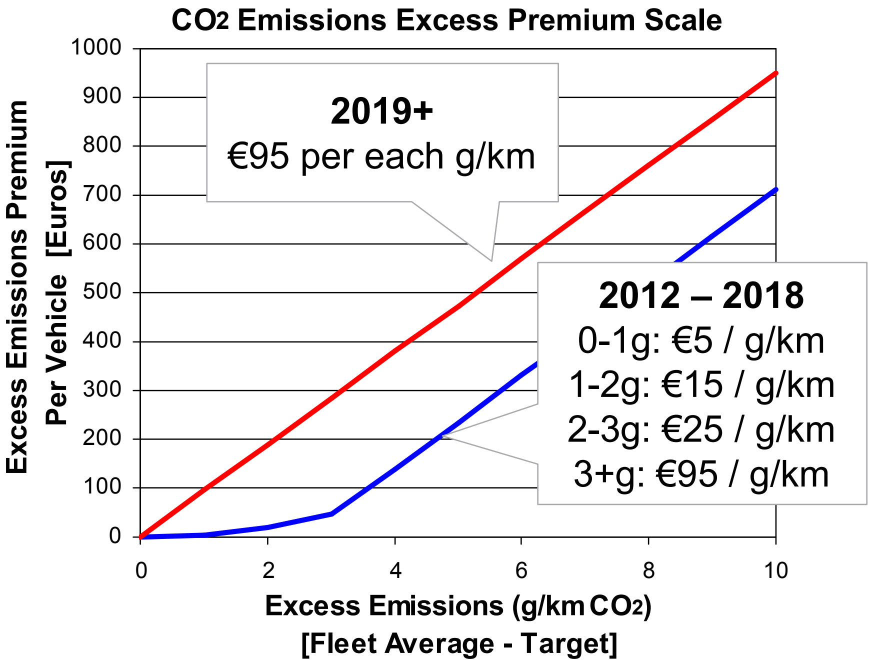
- Applies to European **new passenger cars (M1)**
- **Phase-in** of **130 g/km** standard from **2012 to 2015**

Year	Fleet %
2012	65%
2014	75%
2015	100%

- **Super-credits** for vehicles <50g/km CO_2 (2012 to 2015)
- Long term target of **95g/km** fleet average CO_2 by **2020**
- **Specific CO_2 targets** defined by **vehicle reference mass**
- Targets apply to **manufacturer's fleet average** - no requirement for each individual vehicle to meet its target
- **Pooling** may be carried out between OEMs

Key features of the resolution

- **Penalty scale increases**



Source:"European Parliament Legislative Resolution of December 17, 2008 [TA(2008)0614 DRAFT"

… along with a number of government measures, however as yet there is no such legislation or incentives for Low Carbon HGVs

- £100m to support research, development and demonstration of key technologies for lower carbon vehicles, including electric vehicles
- DfT making £250 million available to create a package of measures to help build a market for ultra low emissions vehicles:
  - £20 million through the low carbon vehicle procurement programme designed to promote the purchase of electric vans for public fleets
  - £500,000 per annum through the Energy Savings Trust to provide grants for the trialling and demonstration of infrastructure for alternative fuels and vehicles
- Government’s Enhanced Capital Allowance (ECA) scheme is designed to encourage businesses to invest in energy-saving equipment, including low carbon dioxide emission cars by allowing them to write off the whole capital cost of their investment in these technologies against their taxable profits in the period in which the investment is made

To understand what measures might be appropriate, the DfT have asked Ricardo to review low carbon technologies for HGVs

Project Objectives

- The principle objectives of the project are to:
  - Review a range of existing and potential low carbon technologies for HGVs including vehicle, powertrain and fuel technologies
  - To make a high level assessment of the costs, benefits and practicality of applying each technology to HGVs including:
    - Determining the technical and commercial feasibility of applying these technologies to HGVs
    - Identifying the potential CO_2 and fuel consumption savings of the technology for standard operating conditions
    - Highlighting the likely impact of the technologies on Technology and environmental costs based on the materials used
    - Highlighting the maturity of the technologies and state of readiness for near, medium and long term CO_2 reduction
  - Identify the extent to which incorporation of these technologies may be used as an indicator to permit monitoring and assessment of CO_2 emissions from HGVs under standard operating conditions
  - Project conductd in a limited 4 week time frame in May 2009 using information available in the public domain at this time

To provide the DfT with a clear picture of both the low carbon technologies available and the feasibility of applying these to HGVs

Source: AEA Proposal

The project uses a three step approach to identify, analyse and summarise applicability of low carbon technologies for HGVs

Project Approach

❶ Technology Identification

- Identify the range of low carbon technologies to be considered
  - Consultation with DfT and Ricardo Experts
  - Group technologies into one of three main themes;
    - Vehicle
    - Powertrain
    - Fuel

❷ Feasibility Analysis

- A feasibility analysis will be conducted for each technology identified which will include:
  - CO_2 and fuel consumption reduction
    - *Over applicable drive cycles for both medium and heavy duty vehicles*
  - Safety and Technology and Environmental Costs
    - *Assessment of cost over baseline vehicle*
    - *Highlight any safety concerns*
  - Technology Limitations
    - *Consideration of practicality of applying each technology to HGVs and any implications this may have on vehicle use*
  - Technology Maturity
    - *Assessment of technology maturity and likely time to market*

❸ Technology Summary

- From the results of the feasibility study a summary table of the cost, benefit and applicability of each technology will be provided
- Consideration will be made as to whether incorporation of the technologies can be used as an indicator for CO_2
- The consistency of CO_2 reduction will be influenced by factors such as:
  - *Driving style/loading characteristics*
  - *Route characteristics*
  - *Reliance on user behaviour (e.g. Filling or availability of a certain fuel)*
  - *Vehicle maintenance*

Source: AEA Proposal

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

- The study was conducted by reviewing and analysing public domain information in addition to the input of Ricardo technical experts
- 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 Emissions Legislation database (EMLEG)
  - 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”

Contents

The low carbon technologies reviewed for application to HGVs are grouped into vehicle, powertrain and fuel themes

Technology Areas

Vehicle

- Low carbon technologies that affect the vehicle body, including wheels, chassis, trailer and cab

Powertrain

- Includes engine, transmission and driveline low carbon technologies
- Technologies include individual components and whole systems

Fuel

- Alternative fuels used to propel the vehicle

For the vehicle theme, technologies lie in the fields of improving aerodynamics, reducing rolling resistance and driver behaviour

Aerodynamics

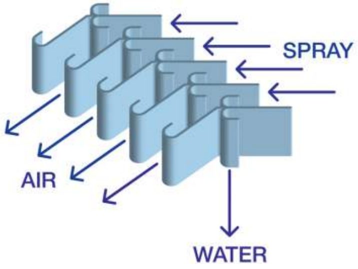
- A number of technologies are being developed which aim to improve the aerodynamics of vehicle trailers to reduce drag and fuel consumption

Aerodynamically Shaped Trailers

Tapering of the trailer to produce lower drag

Aerodynamic Fairings

Addition of trailer and cab fairings to help improve vehicle aerodynamics



Trailer Spray Suppressers

Spray suppressing mudflaps, which help reduce both spray and aerodynamic drag

Rolling Resistance

Low Rolling Resistance Tyres

Incorporation of silica into tyre design to reduce rolling resistance but maintain grip

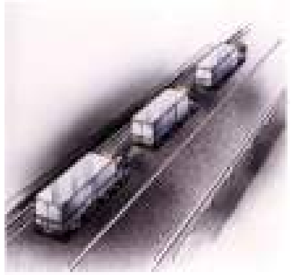
Single Wide Tyres

Replacing standard two thinner wheels with single wide base tyre

Automatic Tyre Pressure Adjustment

Maintains correct tyre pressure for safety and to reduce fuel consumption

Driver Behaviour



Predictive Cruise Control

Using knowledge of the road ahead to control vehicle speed for lowest fuel consumption

Vehicle Platooning

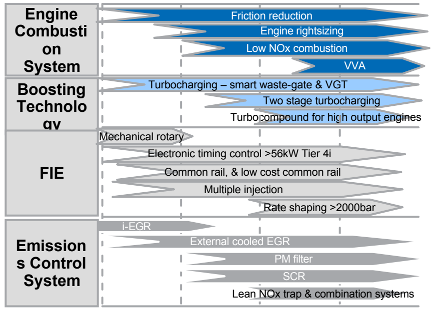
Allowing vehicles to follow safely at speed a close distance to the vehicle in front to reduce fuel consumption

Driver Behaviour

Driver training aimed at improving understanding of fuel efficient and safe driving

For the powertrain theme, engine efficiency is a main area for low carbon technologies grouped into 4 themes

Engine Efficiency

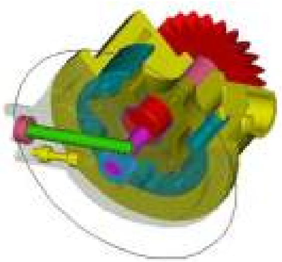


Combustion Systems

- Methods for reducing CO_2 emissions include:
  - *Injection Timing optimisation*
  - *High rate EGR System*
  - *Optimised Inlet Swirl*
  - *Early End of Combustion*
  - *Low Exhaust Back Pressure*
  - *Boost System Matching*
  - *Inlet Manifold Temperature Control*

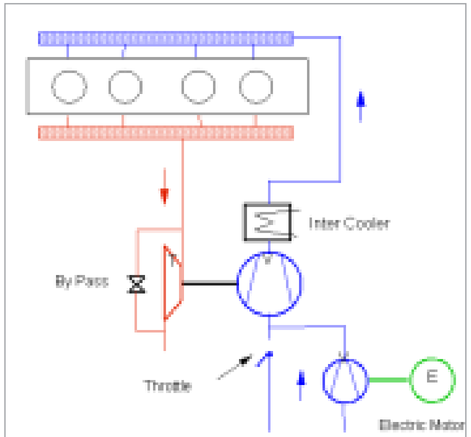
Friction Reduction

- Friction reduction can be achieved through a number of measures:
  - *Lubricant Viscosity Specification*
  - *Piston ring design*
    - *Radial thickness*
    - *Ring tension and liner roundness*
  - *Plasma coated cylinder liner*
  - *Piston skirt – design and coating*
  - *Crank/cylinder axis offset*
  - *Bearing design*



Engine Accessories

- Reduction in parasitic losses of engine accessories
- Examples include:
  - *Air compressor – flow optimisation and electric clutch*
  - *Oil pump – variable flow and electric pump*
  - *Water pump - electric*

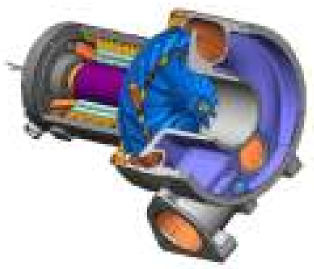


Gas Exchange

- CO_2 reduction can be achieved through improvements in gas exchange handling including;
  - *Electric assisted turbocharger*
  - *Variable valve actuator*
  - *EGR pump*

Waste heat recovery, alternative powertrains and transmissions are the other 3 main areas of low carbon technologies for powertrain

Waste Heat Recovery



- A number of different exhaust heat recovery systems are being developed:
  - Turbocompound – Mechanical drive
  - Turbocompound – turbogenerator
  - Brayton cycle
  - Rankine cycle
  - Thermoelectric generators

Alternative Powertrains

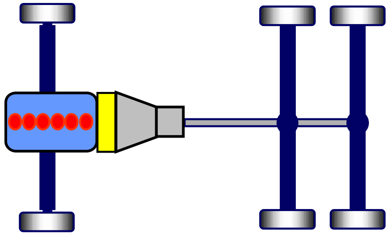
Fuel Cells and Electric Vehicles

- Fully electric vehicles
- Fuel cell vehicles

Hybrid Vehicles

- Hybrid concepts for medium and heavy duty application
- Level of Hybridisation:
  - Stop / Start
  - Full

Transmissions



- Fuel consumption can be reduced through careful matching of rear axle and gear ratios
- Automated transmissions for lower fuel consumption, ensuring optimum shift points:
  - AMT
  - DCT

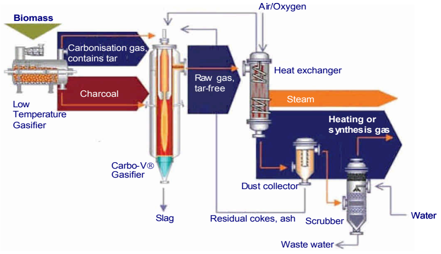
For the fuel theme, biofuels and alternative fuels have been identified for analysis

Biofuel

- Under the banner of biofuels a number of different types of fuels can be considered, which each can use a variety of feedstock
- Current engine technology standards can take up to 5% biodiesel, planned to increase to 7%

FAME

Biodiesel made from esterification of vegetable oils



BTL

Biodiesel created from biomass to liquid process

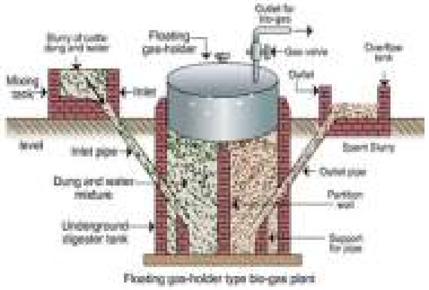
HVO

Biodiesel made from hydrogenation of vegetable oils and animal fats

Alternative Fuels

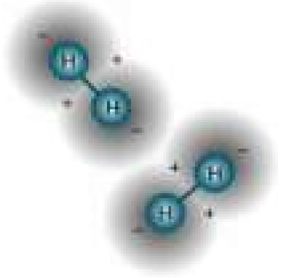
CNG

Compressed Natural Gas



Biogas

Creation of methane from biomass



Hydrogen

Use of hydrogen in internal combustion engines as an alternative fuel

- Note: the fuel that has been focussed on is biodiesel (rather than bio-alcohol) as the prime liquid biofuel for HGVs, since diesel (rather than gasoline) is the dominant fuel type

Contents

HGVs have been divided into medium and heavy duty for feasibility analysis to allow for the differences in typical vehicle operation

- For the purpose of feasibility analysis of low carbon technologies to HGVs, vehicles have been divided into medium duty and heavy duty, which allows for the differences in vehicle operation
- These vehicle types were agreed with DfT at the inception meeting

Medium Duty

- Most common vehicle in the UK is 7.5t 2-axle rigid with a box van type body
- Typical operation tends to be in an urban environment involving frequent stop – start events

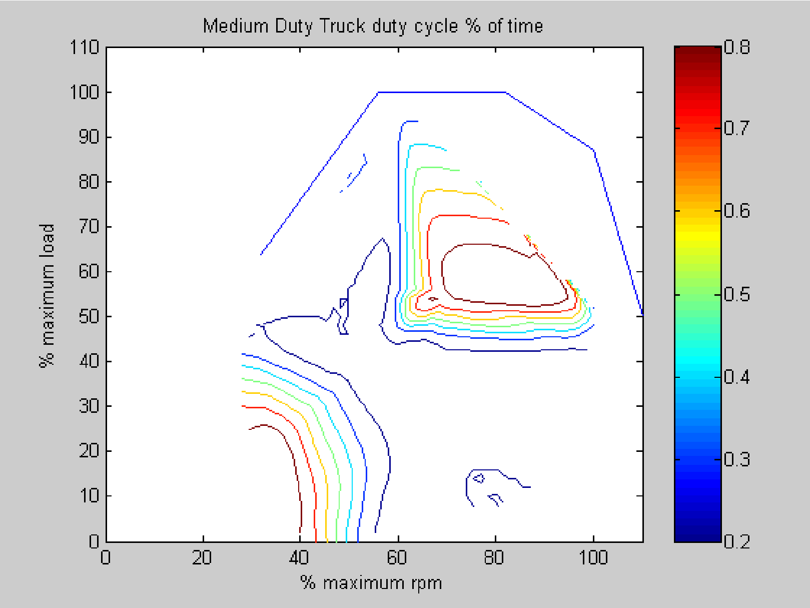
Heavy Duty

- Typically an articulated vehicle, comprising a tractor and trailer with a GVW >32.5 tonnes utilising a three axle configuration
- Typical operation is long motorway journeys at constant speed with little urban driving

A typical medium duty vehicle in the UK is a 7.5t 2-axle rigid, which operates over a predominantly urban cycle with frequent stopping

- Average medium duty truck in the UK is a 7.5t 2-axle rigid, which operates over a predominantly urban drive cycle
- Vehicles are mainly diesel powered with manual transmissions, with AMTs and automatics offered as options

Medium Duty Vehicle Drive Cycle



Medium Duty New Vehicle Benchmark

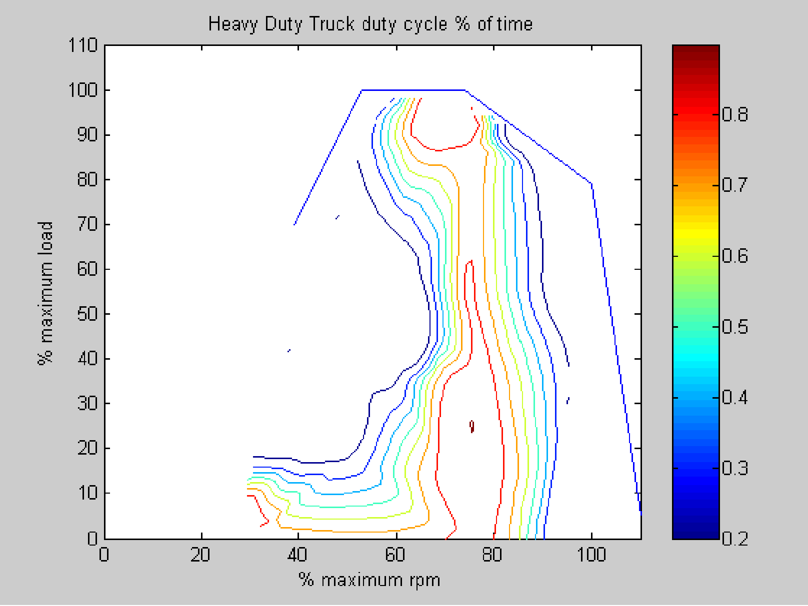
Fuel	Diesel
Engine Capacity (litres)	4.4
Power (kW)	132
Engine Technology	DOHC, L4, DI-CR, TCI. SCR
Fuel Consumption (l/100km)	20.6
Emissions Class	Euro 4
Transmission	Manual 6 (Optional AMT 6 / Auto 5)
Fuel Tank Capacity (litres)	119
AdBlue Tank Capacity (litres)	24
GVW (kg)	7,500
GCW (kg)	11,000
Payload (kg)	4,202
Wheelbase (m)	4
Cab Type	Day

Source: Manufacturers Website, DfT Road Freight Statistics 2007, Ricardo Evaluation

A typical heavy duty vehicle in the UK is a 40t articulated vehicle in a 3-axle configuration used for long haul goods distribution

- A typical heavy duty vehicle in the UK is a 40t articulated vehicle in a 3-axle configuration used for long haul goods distribution
- Vehicles are mainly diesel powered with manual splitter transmissions, with AMTs offered as options

Heavy Duty Vehicle Drive Cycle



Heavy Duty New Vehicle Benchmark

Fuel	Diesel
Engine Capacity (litres)	11.6
Power (kW)	326
Engine Technology	DOHC, L6, DI-UI, TCI. SCR
Fuel Consumption (l/100km)	35.7
Emissions Class	Euro 4/5
Transmission	Manual 14/16 Splitter (Optional AMT)
Fuel Tank Capacity (litres)	450
AdBlue Tank Capacity (litres)	68
GVW (kg)	18,000
GCW (kg)	40,000
Payload (kg)	11,201
Wheelbase (m)	3.7
Cab Type	Sleeper

Source: Manufacturers Website, DfT Road Freight Statistics 2007, Ricardo Evaluation

To ensure a good understanding of the potential of each technology a common rating system was employed (1/3)

- For each technology considered, the impact of the technology in terms of CO_2 benefit, Technology and environmental cost, safety and limitations and technology maturity has been rated from 1 to 10
- The description of these ratings is as follows:

CO_2 Benefit

- 1 = Worst = no CO_2 benefit
- 2 = 1% CO_2 benefit
- 5 = 5% CO_2 benefit
- 8 = 10% CO_2 benefit
- 10 = Best = 30% CO_2 benefit

- CO_2 benefit is given considering tailpipe CO_2 on a per-vehicle basis only. No consideration has been given of fleet mix of vehicle types. With the exception of biofuels, no consideration of lifecycle CO_2 has been possible within the scope of this project

To ensure a good understanding of the potential of each technology a common rating system was employed (2/3)

Technology Cost

- 1 = Worst = 100% additional on-cost relative to incumbent technology (vehicle, powertrain or fuel), not whole vehicle
- 3 = ~ 50% on-cost
- 5 = ~ 10% on-cost
- 7 = ~5% on-cost
- 9 = ~2% on-cost
- 10 = Best = no additional on-cost

- Technology cost considers the additional on-cost of the technology over the incumbent technology and generally does not take into account any lifecycle costs such as maintenance and fuel savings

Environmental Cost

- 1 = Worst = Technology will cause significant damage to the environment during production and disposal
- 3 = Life-cycle environmental impact expected to be worse than incumbent technology
- 5 = Neutral – new technology no better and no worse that incumbent technology
- 8 = Life-cycle environmental impact expected to be better than incumbent technology
- 10 = Best = Life-cycle environmental impact expected to be significantly less than incumbent technology

- Environmental costs make a subjective assessment of the environmental impact of the technology taking into account any different manufacturing processes or materials used which may lead to increased CO_2 emissions during manufacture and whether the technology has benefits of reducing emissions other than CO_2
- No full lifecycle assessment has been conducted

To ensure a good understanding of the potential of each technology a common rating system was employed (3/3)

Safety and Limitations

- 1 = Worst = DO NOT USE this technology
- 2 = Several major safety issues need to be addressed / Several limitations restrict areas of application
- 3 = A few safety issues that need to be addressed / a few limitations restricting application areas
- 5 = No new safety issues, but a few limitations
- 6 = No additional safety concerns or limitations with using this technology
- 7 = No new safety issues, and fewer limitations / more advantages in using the new technology
- 9 = More advantages than disadvantages, and it's safer
- 10 = Best = this technology is much safer to use than the incumbent technology and has far fewer limitations

Technology Maturity

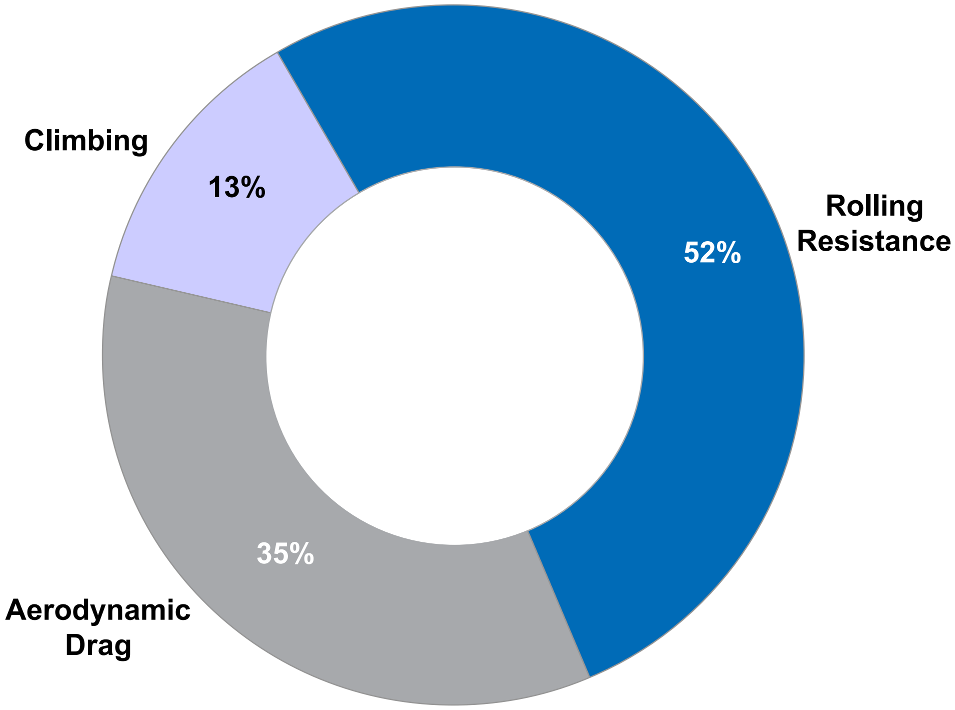
- 1 = University Research Laboratory
- 3 = Technology available but not in HGVs
- 4 = First Prototype in HGVs
- 6 = In Fleet Trials
- 7 = First entry into market
- 10 = Predominant technology in market place

- Safety and limitations considers any safety issues that may be associated with a new technology whether to a person maintaining or operating the vehicle or potential damage to the vehicle and captures, where applicable, any adverse impacts on engine/vehicle durability
- It also covers restrictions that may occur on vehicle usage and loading due to the new technology and issues associated with the introduction of the technology to market

Contents

Rolling resistance and aerodynamic drag represent the largest areas of energy consumption and are the areas targeted for improvement

Energy Distribution for HGV, 44t GVW



- This energy distribution is based on 1,528 km route over 3 days across the UK involving a mix of cross country roads and motorway where vehicles are assessed for acceleration to national speed limit, gradient etc.

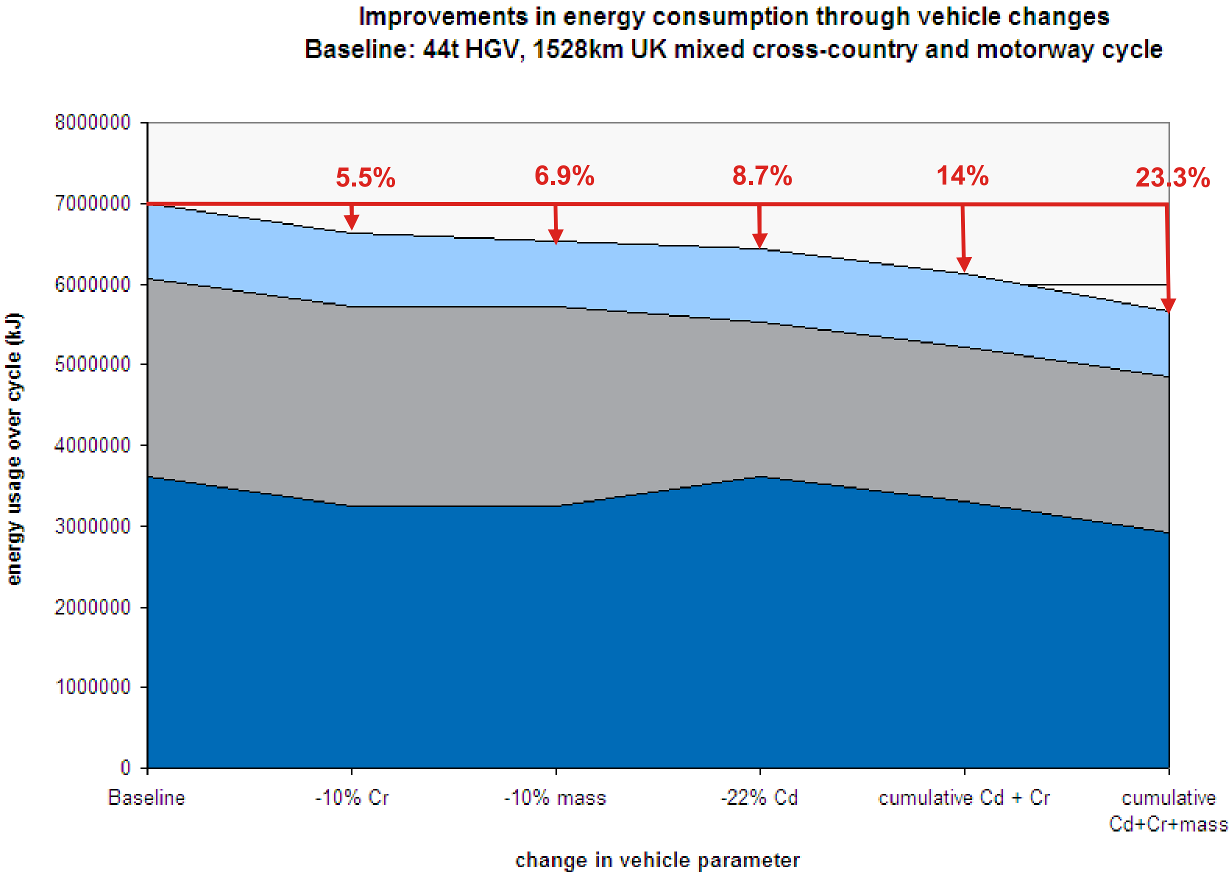
Source: Ricardo Analysis of Commercial Motor information

Key Insights

- Ricardo conducted analysis on a “typical” HGV route – the route used by Commercial Motor magazine to test drive trucks
- Over half, 52%, of energy for the vehicle is used to overcome rolling resistance and a third, 35%, to overcome aerodynamic drag
- Vehicle technologies aimed at reducing rolling resistance and aerodynamic drag can therefore have a large impact on the vehicle fuel consumption

Route marked in colours

Small reductions in rolling resistance and aerodynamic drag can combine to give a large overall benefit in fuel consumption



- For example, using the energy distribution previously given:
  - A 10% reduction in rolling resistance would result in a 5.5% reduction in fuel consumption
  - Likewise a 22% reduction in aerodynamic drag would result in an 8.7% improvement in fuel consumption
- For fuel consumption benefits to be noticeable to fleet owners, benefits need to be in excess of 2% to be out of the usual variations in fuel consumption

Source: Ricardo Research

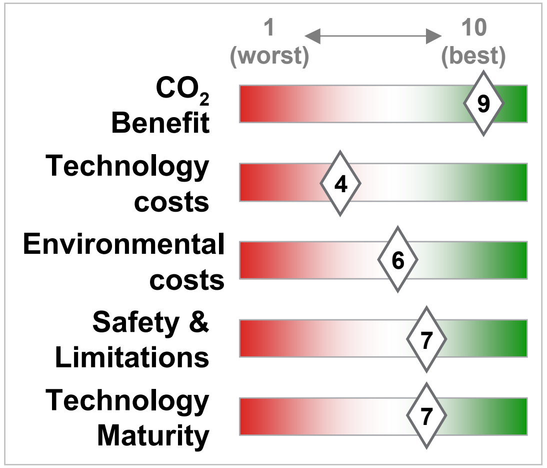
Contents

Aerodynamic trailers have the potential to substantially reduce CO_2 emissions with limited impact on usage, costs and safety

Aerodynamic Trailers

- **Concept:** Aerodynamic trailers using a teardrop shape to reduce aerodynamic drag of vehicle
- **Base Functioning:** Trailers are designed to follow a teardrop shape rising up from standard 4m height of cab to a max. of 4.5m and then reducing to the rear. The design also features full side skirts to help minimise aerodynamic drag
- **CO_2 Benefit:** Average of circa 10% but varies with application and vehicle usage. Most benefit on constant high speed routes
- **Costs:** Typical additional £3k cost with limited environmental impact due to complex manufacturing process for aluminium roof rails

Vehicle



Safety and Limitations

✓ High potential reduction in fuel consumption and CO_2 emissions

✓ Can be used with existing cab design

✓ No impact of vehicle safety

⛔ Loss of load volume for double deck applications

Technology Applicability

- Best suited to long-haul motorway type driving for maximum benefit
- Best suited for applications where use can be made of additional load volume to further improve fleet emissions

Visualisation

Picture: DHL Teardrop trailer (Don-Bur)

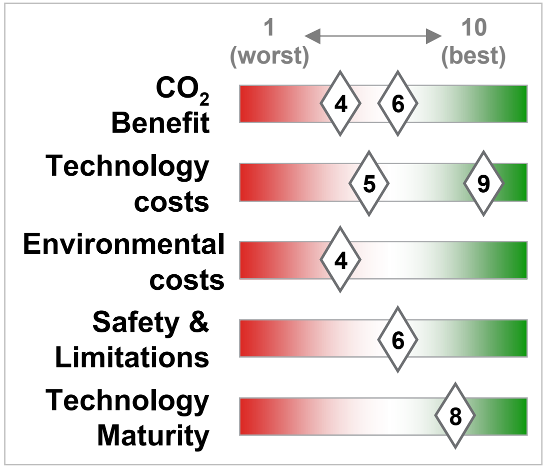
Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

Aerodynamic Fairings can be aftermarket additions to vehicles to improve fuel economy but can be expensive to repair if damaged

Trailer Fairings

- **Concept:** Additional add on‘s to trailers and cabs that help reduce aerodynamics drag and improve fuel consumption
- **Base Functioning:** Technologies include cab deflectors, trailer side skirts and cab collars, all aimed at reducing aerodynamic drag and can be added as aftermarket additions
- **CO_2 Benefit:** This varies with technology and ranges between 0.1% and 6.5% with cab fairings combined with cab collars offering the greatest reduction
- **Costs:** Like CO_2 benefit this also ranges widely from £250 for trailer roof tapering to £1,700 for trailer / chassis side panels

Vehicle



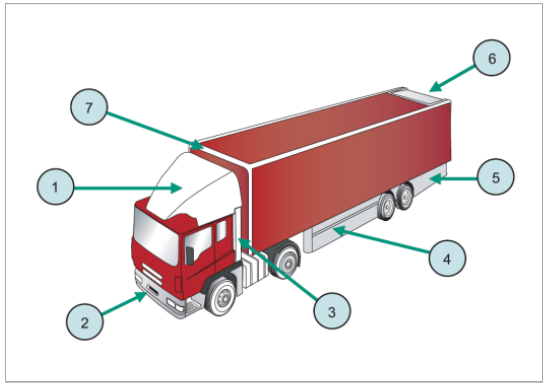
Safety and Limitations

- ✓ Products can be added as aftermarket components
- ✓ The technology presents no new safety risks in application
- ⛔ Addition of aerodynamic fairings adds weight and can reduce the payload
- ⛔ Correct adjustment is required to obtain full benefit and if incorrect can lead to a fuel penalty

Technology Applicability

- Greatest benefit from aerodynamic devices is for vehicles that travel the longest distances at highest speeds
- Cab roof fairings are single most effective technology and still offer benefit for local distribution vehicles

Visualisation



Picture: Examples of truck aerodynamics (Freight Best Practice)

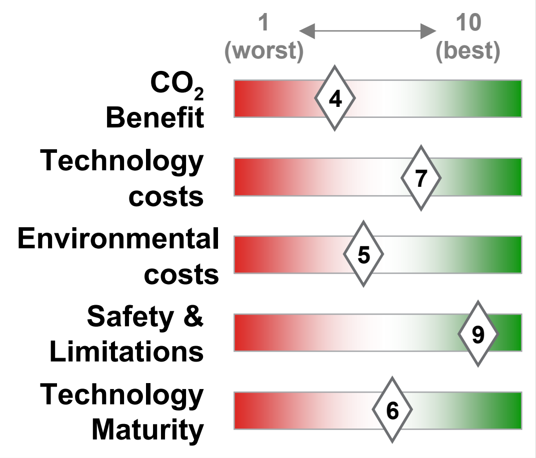
Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

Spray reduction mud flaps both improve road safety and help emissions but benefit is limited by weather conditions

Spray Reduction Mud Flaps

- **Concept:** Spraydown has developed a air water separator mud flap, which reduces spray by 40% and also has aerodynamuic benefits
- **Base Functioning:** The mud flap separates the water from the air through a series of vertical passages created by vanes which makes the spray change direction a number of times eliminating the water
- **CO_2 Benefit:** Estimated to be around 3.5%
- **Costs:** Costs are estimated to be an additional £2 per unit

Vehicle



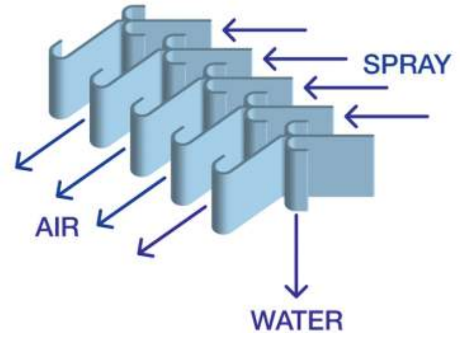
Safety and Limitations

- ✓ Reduces vehicle spray by a significant amount improving road safety for other uses
- ✓ Conforms to required legislation
- ✓ Benefit for fuel consumption reduction is independent of weather conditions
- ✓ Can be fitted to any standard mud wing

Technology Applicability

- Greater applicability to heavy duty vehicles as most benefit at high constant speeds
- Can be applied to all vehicle and trailer types

Visualisation



Picture: www.spraydown.com

Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

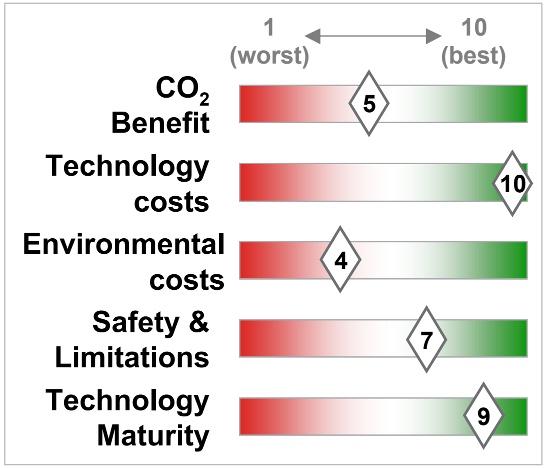
Contents

Low Rolling Resistance Tyres are widely available in the market and able to provide 5% CO_2 benefit at no additional purchase cost

Low Rolling Resistance Tyres

- **Concept:** Tyres specifically designed to lower rolling resistance
- **Base Functioning:** Tyre design to minimise rolling resistance whilst still maintaining the required levels of grip
- **CO_2 Benefit:** Achievable CO_2 benefit depends on the number of tyres replace but trials suggest 5% is possible
- **Costs:** Limited evidence suggests that there may be no additional cost for low rolling resistance tyres, but tyre lifespan is lower

Vehicle



Safety and Limitations

- ✓ Performance of low rolling resistance tyres is comparable to that of standard tyres
- ✓ Low rolling resistance tyres do not have an impact on vehicle functionality
- ⛔ Specific low rolling resistance tyres are only available for long haul applications where benefit will be greatest
- ⛔ Benefit reduces as tyres wear

Technology Applicability

- Technologies tend to be aimed at long distance vehicles rather than vehicles operating over an urban cycle

Visualisation

Picture: Michelin XZA 2 Energy

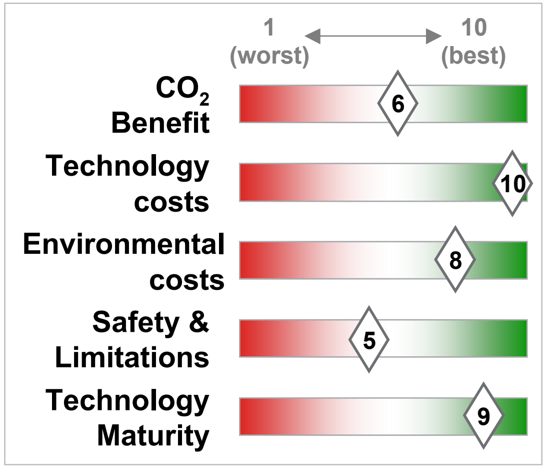
Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

Single Wide Tyres offer an increase in payload along with a reduction in fuel consumption but fitment is limited by legislation

Single Wide Tyres

- **Concept:** Replacement of dual tyres to a single wide tyre
- **Base Functioning:** Single wide tyres with lower aspect ratio which can replace dual tyres on an axle
- **CO_2 Benefit:** 2% reduction for single tractor axle and between 6% to 10% for whole vehicle
- **Costs:** A single wide tyre is approximately the same as two thinner tyres and has similar life span

Vehicle



Safety and Limitations

✓ Lighter weight increasing payload

✓ Tyre wear rate comparable to conventional tires

⛔ Legislation requires twin wheels on the drive axle of vehicles over 40 tonnes

⛔ Requires fitment of a tyre pressure monitoring system

⛔ Increased damage to roads, particularly those with a thin top layer

  – Initial tests on new generation wide-base tyres indicates single wide are no worse than standard

Technology Applicability

- Most applicable for vehicles travelling long distances
- More benefit for applications where payload increase is of benefit

Visualisation

Picture: Michelin X One (Michelin Corporate Website)

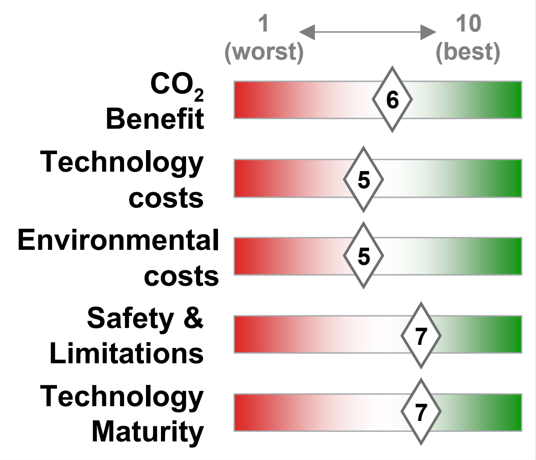
Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

Automatic Tyre Pressure Adjustment monitors and adjusts tyre pressures to improve tyre safety and reduce fuel consumption

Automatic Tyre Pressure Adjustment

- **Concept:** Automatic tyre pressure monitoring automatically monitors and adjust tyre pressures
- **Base Functioning:** Automatic Tyre Pressure systems use the air compressor on the vehicle to automatically monitor and adjust tyre pressures to optimum levels for load and terrain conditions
- **CO_2 Benefit:** Estimated to be 7 – 8% based on the typical volume of vehicles running with under inflated tyres
- **Costs:** Cost for purchase and installation is circa £10,000 and the system can be re-fitted to second and third generation vehicles

Vehicle



Safety and Limitations

- ✓ Systems can be reused on second and third generation vehicles, improving the return on investment
- ✓ Reduction in tyre replacement and maintenance costs due to reduced tyre wear and vibration
- ✓ Tyre wear improved with much more even wear on drive axles
- ✓ Improved safety due to lower tyre wear

Technology Applicability

- Applicable to all vehicles, but benefit likely to be greatest on high mileage vehicless and those operating on a range of different terrains

Visualisation

Picture: Automatic Tyre Pressure System (Freight Best Practice)

Source: Freight Best Practice Scotland, Innovation in Scottish Timber Haulage: Tyre Pressure Control Systems (TPCS), April 2009 – Full sources available on detail slides in the attached annex

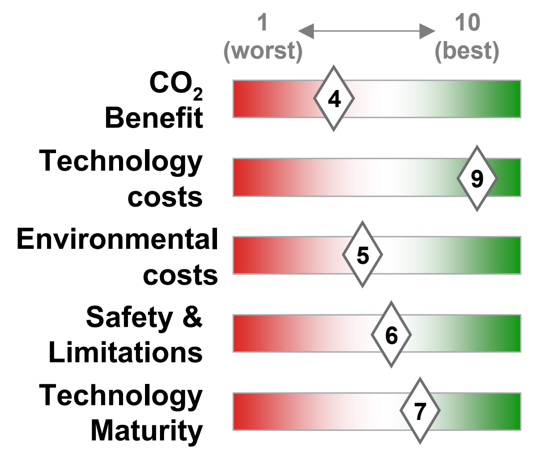
Contents

Predictive Cruise Control is a new to market technology which uses knowledge of the road ahead to optimise fuel consumption

Predictive Cruise Control

- **Concept:** Development of systems that use electronic horizon data to improve the fuel efficiency of vehicles
- **Base Functioning:** Combining GPS with Cruise Control to better understand the road ahead for optimal speed control
- **CO_2 Benefit:** Initial reports indicate fuel economy benefits in the range 2 – 5% but this will vary with route
- **Costs:** No cost information is available but not anticipated to be higher than existing GPS and crusie control

Vehicle



Safety and Limitations

- ✓ The technology can be applied to any truck without limiting usage, although has greater benefit for long haul
- ✓ Technology has no new safety implications over standard cruise control
- ⛔ Journey times can increase due to greater speed variations below set speed

Technology Applicability

- Most applicable to long haul vehicle apllications where cruise control is used most often

Visualisation

Picture: Freightliner Cascadia (www.freighliner.com)

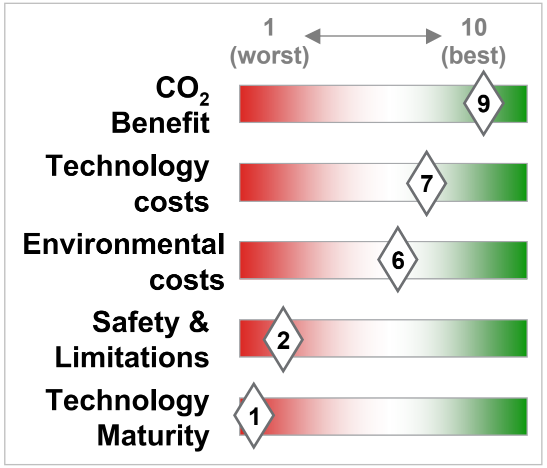
Source: Freightliner debuts RunSmart Predictive Cruise Control, Autoblog, March 22nd 2009; SAE Paper 2004-01-2616, The Predictive Cruise Control – A System to Reduce Fuel Consumption of Heavy Duty Trucks; Hellstroem, Erik, Explicit use of road topography for model predictive cruise control in heavy trucks, 21st February 2005 – Full sources available on detail slides in the attached annex

Vehicle platooning has potential for CO_2 savings but has significant legislative and safety barriers to overcome for commercialisation

Vehicle Platooning

- **Concept:** Vehicle driving in close proximity to each other to create a train
- **Base Functioning:** Vehicles are able to follow each other closely and safely to reduce aerodynamic drag and fuel consumption and increase safety
- **CO_2 Benefit:** In the region of 20% for motorway speeds
- **Costs:** Anticipated costs of around £305 – £1,600 for additional sensors and active safety features required toimplement the technology

Vehicle



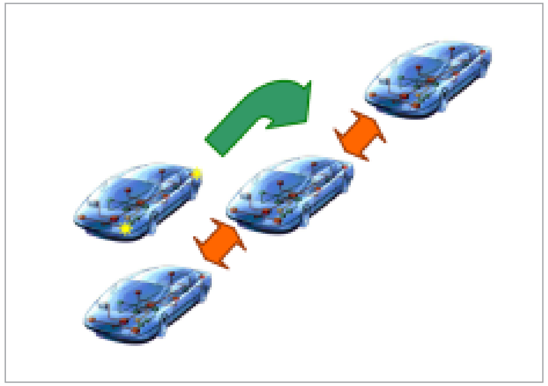
Safety and Limitations

✓ Automated driving increases comfort
✓ Added value when not in a platoon: sensors can be used for active safety
✓ Lower operating costs
⛔ No impact on vehicle functionality
⛔ Liability issues associated with autonomous vehicle control
⛔ Contravenes current road regulations
⛔ System performance in adverse driving conditions
⛔ Risk of driver underload and of copy cat driving outside the platoon

Technology Applicability

- Greatest benefit is at higher vehicle speeds such as motorway driving
- This technology is therefore more applicable to long haul HGVs where there is a greater business case

Visualisation



Picture: SATRE FP7 Proposal

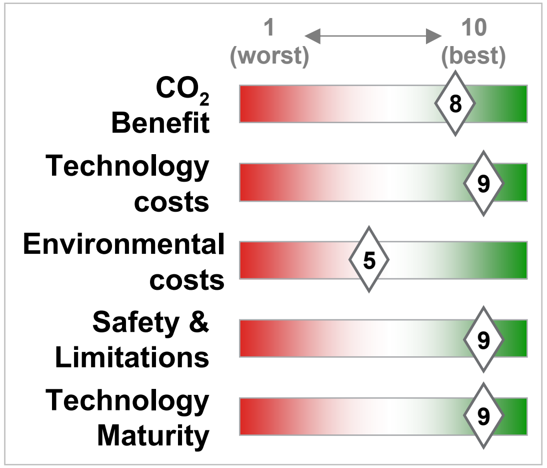
Source: Ricardo Research, Ricardo Evaluation – Full sources available on following detail slides

SAFED is a well established UK driver training scheme aimed at safe and fuel efficient driving and is applicable to all vehicles

Driver Behaviour

- **Concept:** Driver training for improved fuel economy and safety
- **Base Functioning:** SAFED is a driver training scheme aimed at improving accident prevention and reduction and fuel consumption through both practical and theory
- **CO_2 Benefit:** This varies with driver, but from case studies of all drivers trained it averages at circa 10%**. However, effectiveness is expected to fall off with time after the initial training session**
- **Costs:** The cost of SAFED training varies from £150 to £300 per session

Vehicle



Safety and Limitations

- ✓ Enhanced safe-driving techniques
- ✓ Gear changes reduced by around one-third on test run through block-shifting
- ✓ Drivers feeling more relaxed at the end of the working day
- ✓ No increase in journey time
- ✓ No limitations on vehicle usage
- ⛔ Effectiveness falls off with time after the initial training session

Technology Applicability

- SAFED is applicable to any HGV driver and all duty cycles

Visualisation

Picture: SAFED logo (www.safed.org.uk)

Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

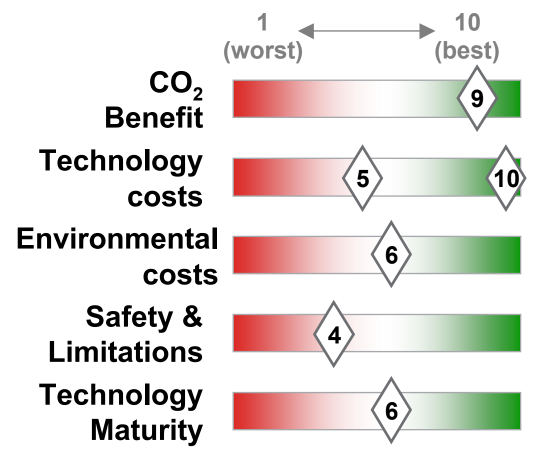
Contents

The use of alternative power for vehicle bodies has good CO_2 reduction potential, however some systems are significant on cost

Electric/ Alternative Fuel Bodies

- **Concept:** Replacement of existing power sources for vehicle bodies which use diesel for power
- **Base Functioning:** Electrification or use of an alternative power source, e.g. nitrogen to drive systems requiring power instead of diesel
- **CO_2 Benefit:** Varies between 10% and 20% depending on the body power system being replaced
- **Costs:** Up to 15% vehicle on cost, but some systems are lower cost

Vehicle



Safety and Limitations

- ✓ No limitations on vehicle usage
- ✓ Electric and nitrogen systems offer quieter and smoother operation
- ✓ Electric and nitrogen systems have low operating and maintenance costs
- ✓ Nitrogen system, unlike mechanical – will not 'top freeze'
- ⛔ Safety of nitrogen system

Technology Applicability

- Suited to applications where electrical motors have sufficient torque to drive load
- For use in hybrid vehicle applications where hybrid battery can be used to power trailer

Visualisation

Picture: Volvo Hybrid Refuse Truck (gizmag)

Source: Ricardo Research, Ricardo Evaluation; http://www.gizmag.com/worlds-first-hybrid-refuse-truck-volvo-sweden/9131/ – Full sources available on detail slides in the attached annex

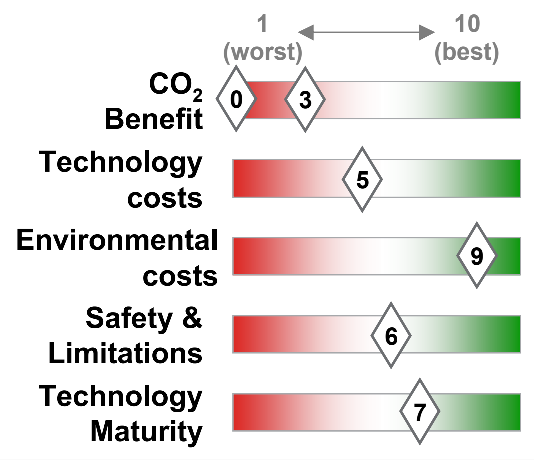
Contents

Combustion system optimisation essential to achieve emissions legislation and maintain competitive fuel consumption

Combustion System Optimisation

- **Concept:** Improvements in combustion system efficiency with further development of the combustion system:
  - Higher pressure FIE, high capability air/EGR systems
- **Base Function:** Optimise NOx-BSFC trade-off when moving to next emissions level. Possibility to improve BSFC at a given emissions level by early adoption
- **CO_2 Benefit:** Theoretical maximum of 3% in BSFC (assuming moving from “worst“ to “best“ technology at the same emissions level). However real figures likely to be much lower (1-2%) and can be strongly masked by vehicle application
- **Costs:** Adding costs in technology for powertrain at each emissions level

Powertrain



Safety and Limitations

✓ Technology available up to Euro 6 with no fuel consumption penalty

✓ No impact of vehicle safety

⛔ Low potential for CO_2 reduction, especially if manufacturers are already using these technologies

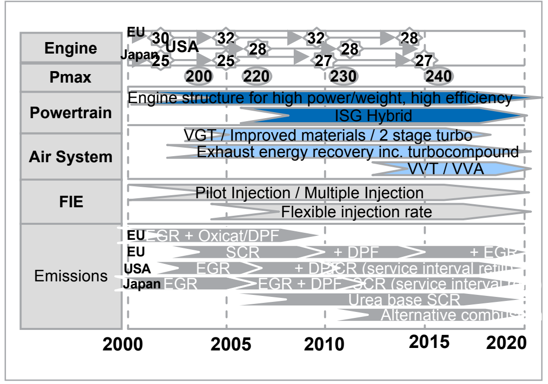
⛔ Essential engine/powertrain development to achieve legislative emission regulations

⛔ Poorly integrated aftertreatment can lead to a fuel consumption/CO_2 penalty

Technology Applicability

- Technology for Euro 5 in production – lower FC compared to Euro 4
- Euro 6 technology in development status
- Diminishing returns as we move to lower emissions
- Industry resistant to anything which might be seen to mandate particular technologies to meet emissions limits
- Very difficult to use as a proxy for CO_2 reductions because of the complex trade-offs

Visualisation



Picture: Ricardo Research, Ricardo Evaluation

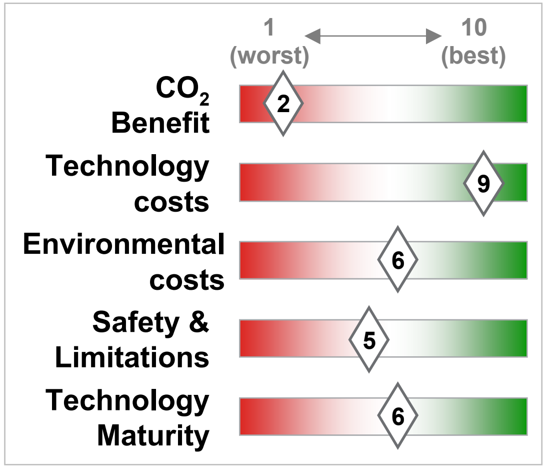
Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

Lowering engine friction can improve CO_2 emissions, but the overall impact on engine friction versus CO_2 emissions is rather small

Combustion System Optimisation

- **Concept:** Improvements in engine efficiency by reducing engine friction
- **Base Functioning:** - Reduction in engine friction with improvements in piston, piston ring and cylinder liner package as well as crankshaft system in design and surface finish. Improved manufacturing processes
  - Crankshaft / Cylinder axis off-set to reduce force at cylinder fire condition (re-design base engine & production line)
  - Reducing engine oil viscosity and introducing oil additives
- **CO_2 Benefit:** - Potential 0.5 % reduction in FC for design and surface improvements
  - Oil specification change with an average ~1.5%
- **Costs:** Adding costs in technology for powertrain and complicating production process

Powertrain



Safety and Limitations

✓ Technology available

✓ No impact of vehicle safety

⛔ Low potential for CO_2 reduction

⛔ Crankshaft/Cylinder off-set only for new engine designs

⛔ Durability concerns with low viscosity grade oils

⛔ Not all low viscosity grade oils behave the same

Technology Applicability

- Technology partly introduced in light duty applications
- Low engine friction high importance for new engine design programmes

Visualisation

Picture: Heavy duty piston

Source: Infineum, Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

Optimisation or electrification of engine accessories has potential to reduce CO_2 emissions for medium and heavy duty applications

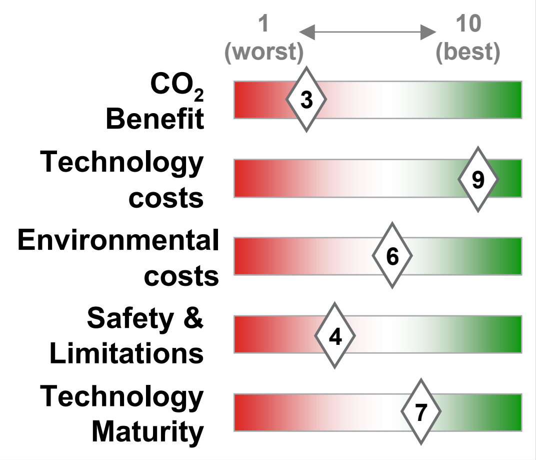
Controllable air compressor

- **Concept:** Electric clutch – air compressor
- **Base Functioning:** Air compressor with electric / air actuated clutch to de-connect compressor in idle status or when compressor not required

  Current truck airbrake systems simply dump excess pressure to ambient when the air tanks are full, the compressor keeps running

  For long-haul truck work, the airbrake system may not be used for up to 90% of the time
- **CO_2 Benefit:** Average of 1.5 % CO_2 reduction
- **Costs:** Increasing costs – electric clutch and control system

Powertrain



Safety and Limitations

✓ Medium potential reduction in fuel consumption and CO_2 emissions

✓ Can be used with existing engine design

⊖ Increased costs

⊖ System must be fail safe

Technology Applicability

- Available for heavy duty application and in series production (MAN)
- Medium duty applications possible – might be less effective (more stop / start scenario)

Visualisation

Picture: Transport Engineer, Every little helps, Nov 2008

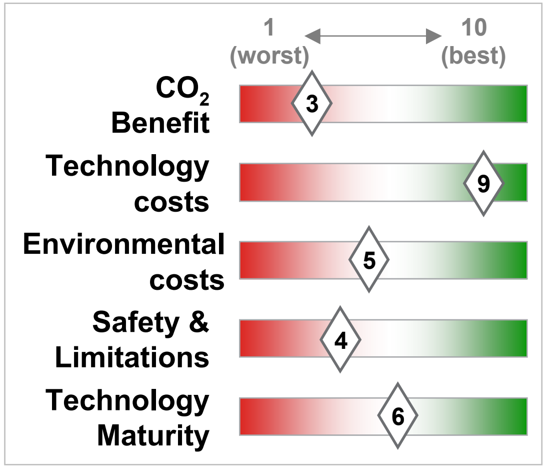
Source: Ricardo Research, Ricardo Evaluation, Transport Engineer, Every little helps, Nov 2008 – Full sources available on detail slides in the attached annex

Optimisation and electrification of engine accessories have potential to reduce CO_2 emissions for medium and heavy duty applications

Accessories – Oil pump

- **Concept:** Oil pump – variable speed pump or electric oil pump
- **Base Functioning:** Oil flow amount adjusted to engine speed and requirement to optimise oil flow and oil pump power consumption
- **CO_2 Benefit:** Fuel consumption / CO_2 improvements 1-3% possible
- **Costs:** Increasing costs – advanced oil pump technology and control systems

Powertrain



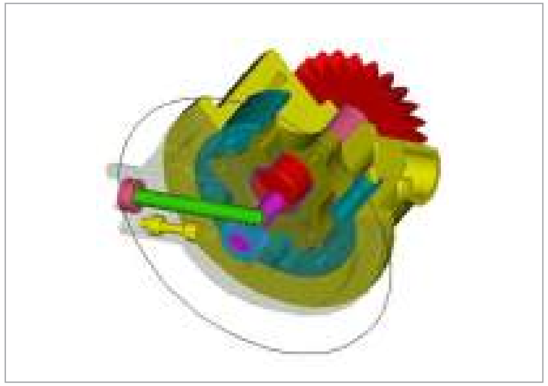
Safety and Limitations

- ✓ Moderate potential reduction in fuel consumption and CO_2 emissions
- ✓ New engine designs
- ✓ No impact of vehicle safety for mechanical variable flow pumps providing they fail safe
- ⛔ Applicability to existing engines
- ⛔ Durability concerns with full electric oil pumps
- ⛔ Increased costs

Technology Applicability

- Variable speed pumps available and in production medium and heavy duty vehicles
- Electric oil pumps not in series production
- Demonstrator and reasearch projects

Visualisation



Picture: www.concentric-pump.co.uk

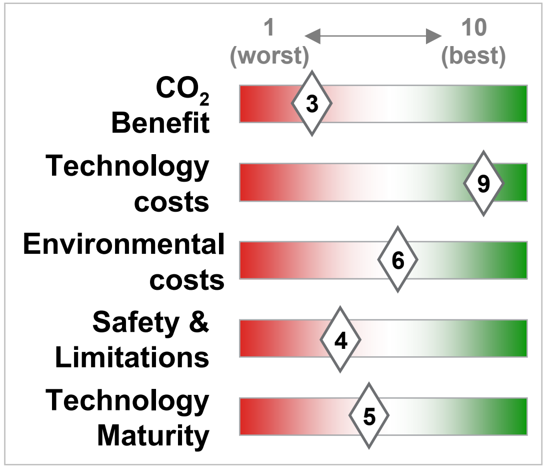
Source: Ricardo Research, Ricardo Evaluation; http://www.concentric.co.uk – Innovations oil pump, May 2009 – Full sources available on detail slides in the attached annex

Optimisation and electrification of engine accessories has potential to reduce CO_2 emissions for medium and heavy duty applications

Variable flow water pump – electric water pumps

- **Concept:** Variable coolant flow depending on engine speed / load condition
- **Base Functioning:** Mechanical variable flow and electric water pumps vary pump speed, hence coolant water flow according to the engine demand
- **CO_2 Benefit:** Estimated 0.7% improvement in fuel economy / CO_2 emissions with variable flow water pump (mechanical) and about 1% - 4% with an electric water pump
- **Costs:** Increasing costs for both pump types

Powertrain



Safety and Limitations

✓ Medium potential reduction in fuel consumption and CO_2 emissions

✓ Up-date on existing designs with mechanical variable flow pumps

✓ No impact of vehicle safety

⛔ Fully electric pumps for new engine designs

⛔ Increased costs

⛔ Pump must fail safe

Technology Applicability

- Available for heavy duty application and intended for production in 2009 by Mercedes (mechanical variable flow pumps)
- Medium duty applications may acquire technologies form light duty sector

Visualisation

Example of an electric coolant pump.

Picture: *www.daviescraig.co.au*

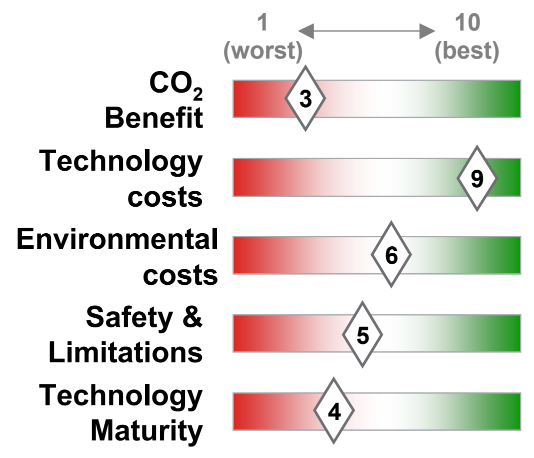
Source: Ricardo Research, Ricardo Evaluation; *www.daviescraig.co.au* – Full sources available on detail slides in the attached annex

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

Air hybrid system – Pneumatic booster system (PBS)

- **Concept:** Compressed air to inject in air system
- **Base Functioning:** Compressed air from vehicle braking system injected rapidly into the air path and allows a faster vehicle acceleration, which allows an earlier gear shift (short shifting). Engine operates more in efficient engine speed / load range
- **CO_2 Benefit:** ~1.5-2 % CO_2 reduction claimed, will depend on base engine BSFC map characteristic, ability of system to support repeated short shifts and efficiency of generating compressed air in the first place
- **Costs:** Expected moderate cost increase

Powertrain



Safety and Limitations

- ✓ Medium potential for CO_2 reduction
- ✓ System demonstrated on buses and trucks
- ⛔ System must not risk loss of air from brakes
- ⛔ Boost limitations on air system (regulating to maximum boost limit)
- ⛔ Air compressor with higher capacity
- ⛔ Larger air reservoir tank

Technology Applicability

- PBS system developed by Knorr-Bremse
- Series production expected to start 2011

Visualisation

Picture: Knorr-Bremse PBS system; Knorr-Bremse; 29th IWM, 2008 1)

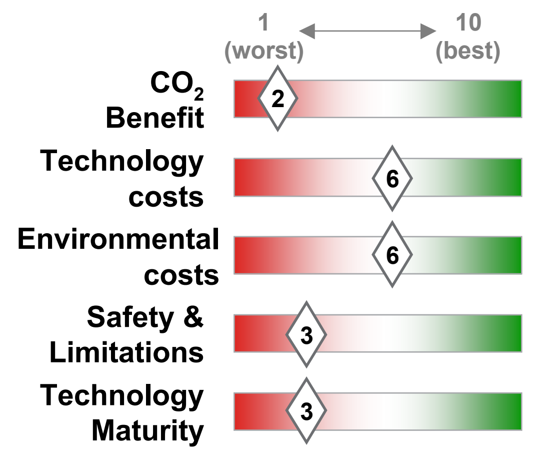
Source: Ricardo Research, Ricardo Evaluation; 1) PBS; Dr. Ing. H. Nemeth, et al, Knorr-Bremse, 29th International Vienna Motor Symposium 2008 – Full sources available on detail slides in the attached annex

Gas exchange improves engine efficiency and has potential to improve CO_2 emissions

Gas exchange – Efficiency Improvement

- **Concept:** Improvement engine efficiency via less gas exchange losses
- **Base Functioning:** Combination of technologies to increase fresh air and exhaust gas exchange rate and lowering the exhaust backpressure:
  - Two stage turbocharging
  - Electric assisted turbocharger increase the fresh air intake over the speed range
  - Variable valve train, adjusting valve timing to engine speed
  - Long route EGR or EGR pump, which also increases energy available to turbocharger
- **CO_2 Benefit:** Up to 2 % CO_2 reduction
- **Costs:** Expeceted high cost increase for technology package

Powertrain



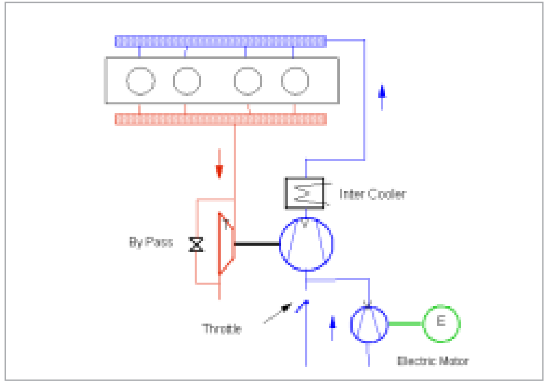
Safety and Limitations

- ✓ Two stage turbocharging established in the market
- ✓ VVT required for HCCI combustion systems
- ⛔ Cost and durability EGR pump and electrical valve actuation systems
- ⛔ Lower engine speed range on heavy duty engines – less efficient for VVT
- ⛔ Power source for electric motor
- ⛔ Air system specification driven by emissions

Technology Applicability

- Two stage turbocharging mature
- Heavy duty VVT systems in research phase
- Electrical assisted turbochargers researched in light duty field
- EGR pump in research / development status

Visualisation



Picture: Electric assisted turbocharger
Source: www.3k-warner.de

Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

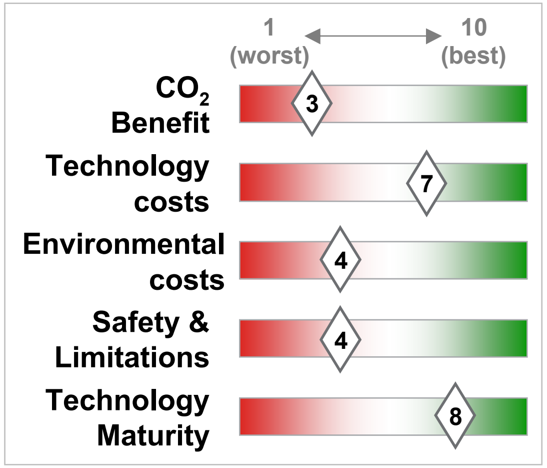
Contents

Waste heat recovery with moderate potential for CO_2 reductions – exhaust recovery systems: Turbocompound mechanical drive

Waste recovery systems – mechanical turbocompound

- **Concept:** Exhaust gas energy recovery
- **Base Functioning:** Exhaust gas energy recovery with addtional exhaust turbine, which is linked to a gear drive and transfers the energy on to the crankshaft providing extra torque.
- **CO_2 Benefit:** Overall fuel economy benefit of 3-5% achieveable[1)]
- **Costs:** Increasing costs for turbocompound system

Powertrain



Safety and Limitations

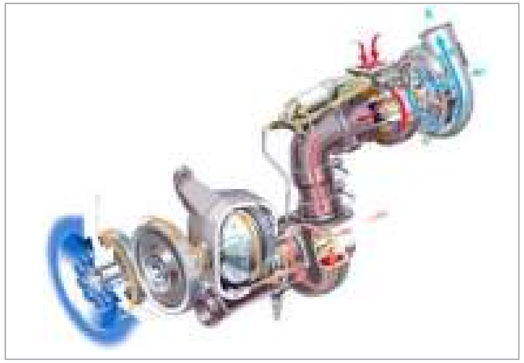
- ✓ Medium to high potential in reduction of fuel consumption and CO_2 emissions
- ✓ Primary for new engine designs
- ✓ No impact of vehicle safety

- ⛔ Complicated gear drive (turbine, engine speed difference)
- ⛔ Increased costs

Technology Applicability

- Available for heavy duty application (Scania, Volvo, Detroit Diesel)
- Fuel / CO_2 benefits confirmed
- Medium duty applications not in production and benefits might be less significant depending on drive cycle

Visualisation



Picture: *Scania turbo compound system Source: www.scania.com*

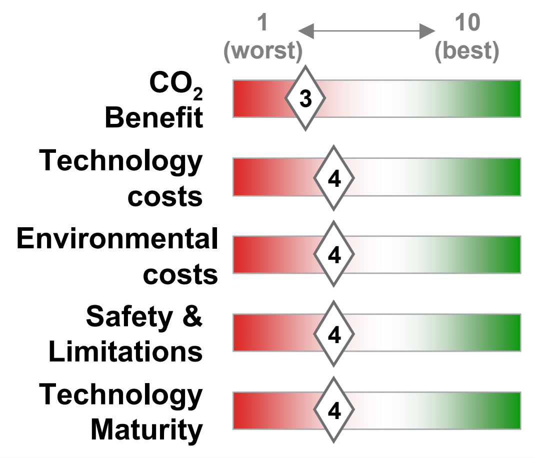
Source: Ricardo Research, Ricardo Evaluation; 1) http://www.theicct.org/documents/Greszler_Volvo_Session3.pdf Turbocompound; Presentation ICCT / Volvo Feb 2008 – Full sources available on detail slides in the attached annex

Waste heat recovery with moderate potential for CO_2 reductions – exhaust recovery systems: Electrical Turbocompound

Waste recovery systems – electrical turbocompound

- **Concept:** Exhaust gas energy recovery
- **Base Functioning:** Exhaust turbine in combination with an electric generator / motor to recover exhaust energy
  - Recovered energy can be stored or used by other electrical devices
  - Motor during transients to accelerate
- **CO_2 Benefit:** Fuel economy benefit of 10 % achieveable at maximum power point[1]. Real world benefit closer to 3% depending on duty cycle. ETC perhaps best suited to off-highway applications like ploghing tractor which runs a long time at max power
- **Costs:** Increasing costs for turbocompound system

Powertrain



Safety and Limitations

✓ Moderate potential in reduction of fuel consumption and CO_2 emissions

✓ Primary for new engine designs

⊖ Added complexity for energy storage, control

⊖ Increased costs generator turbine, energy storage, crank mounted motor

⊖ High voltage system

Technology Applicability

- Electric turbocompounding systems for medium and heavy duty application in developement phase
- Fuel / CO_2 benefits confirmed

Visualisation

Picture: John Deere- Bowman Power turbogenerator
Source: http://www1.eere.energy.gov DEER 2006

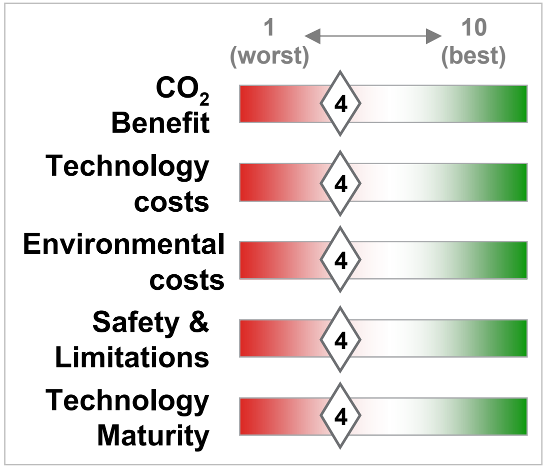
Source: Ricardo Research, Ricardo Evaluation; 1) *http://www1.eere.energy.gov;* Electric turbocomponding; John Deere; DEER 2006 – Full sources available on detail slides in the attached annex

Waste heat recovery with high potential for CO_2 reductions – exhaust recovery systems: heat exchanger

Waste recovery systems – heat exchanger

- **Concept:** Exhaust gas energy recovery with heat exchangers. Sometimes called “bottoming cycles“ (power station terminology, as it takes out low grade heat from the “bottom” of the thermodynamic cycle)
- **Base Functioning:** Exhaust gas heat used in exchanger to drive an additional power turbine to generate energy
  - Brayton cycle
  - Rankine cycle
- **CO_2 Benefit:** 3-6% CO_2 / fuel economy benefit depending on cycle and turbine efficiency
- **Costs:** Depending on technology,

Powertrain



Safety and Limitations

- ✓ High potential in reduction of fuel consumption and CO_2 emissions
- ✓ Depending on cycle (exchanger) and turbine efficiency
- ⛔ Addtional working fluid (Rankine cycle)
- ⛔ Added complexity for energy storage, control, packing
- ⛔ Increased costs heat exchanger, high efficiency turbine,
- ⛔ High voltage system

Technology Applicability

- Research phase
- Intruction in heavy duty application might be easier due to packaging

Visualisation

Picture: Caterpillar package layout – Brayton system[1)]

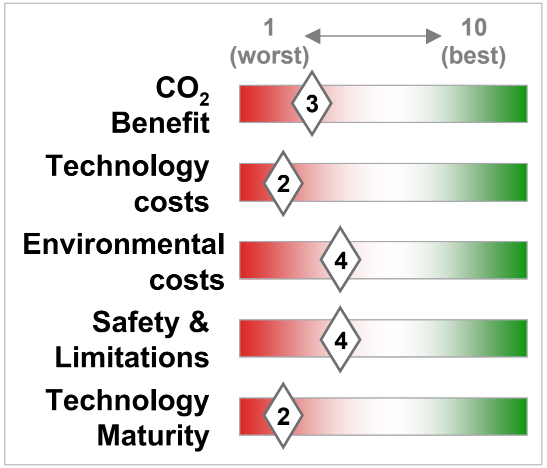
Source: Ricardo Research, Ricardo Evaluation; 1) http://www1.eere.energy.gov; Kruiswyk; Exhaust waste heat recovery, Caterpillar; DEER 2008 - – Full sources available on detail slides in the attached annex

Waste heat recovery with potential for CO_2 reductions – exhaust recovery systems: thermo-electric processes

Waste recovery systems – thermoelectric generators

- **Concept:** Exhaust gas energy recovery with thermoelectric heat exchangers
- **Base Functioning:** Thermoelectric generators using Seebeck effect, creating a voltage at the present of a temperature difference in between two different metals or semiconductors. Direct conversion of heat to electricity. Nearly 25% of fuel energy is typically lost to the exhaust stream. Typically implemented using extremely advanced materials: SiGe quantum dots/wells, nanomaterials, PbTe wafers, filled Skutterudites (CoAs3 based crystal lattices), Mischmetal (cheap naturally occurring CeLa alloy)
- **CO_2 Benefit:** ~2 % CO_2 / fuel economy benefit
- **Costs:** Significant at current research level

Powertrain



	1 (worst) ↔ 10 (best)
CO_2 Benefit	3
Technology costs	2
Environmental costs	4
Safety & Limitations	4
Technology Maturity	2

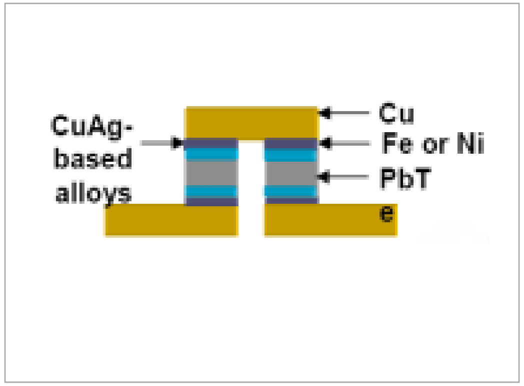
Safety and Limitations

- ✓ Medium potential in reduction of fuel consumption and CO_2 emissions
- ⛔ Technology depending on development of materials with high merit figure in a realisable manufacturing process
- ⛔ High costs for materials and processing
- ⛔ Low TE module conversion efficiencies with actual bulk materials

Technology Applicability

- Research phase

Visualisation



Picture: Layout thermoelectric generator, Ed Gundlach GM DEER 2008

Source: Ricardo Research, Ricardo Evaluation – Full sources available on detail slides in the attached annex

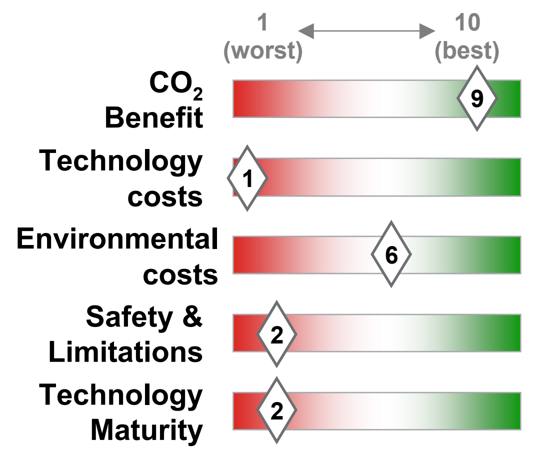
Contents

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

Fuel Cell Powertrains

- **Concept:** Fuel cells are often viewed as the powertrain of the future. Fuel cells convert the chemical energy of hydrogen into electrical energy that can be used to power the vehicle.
- **Base Functioning:** A hybrid Polymer Electrolyte Membrane (PEM) fuel cell system is used as the prime mover for the vehicle
- **CO_2 Benefit:** PEM FC systems run on hydrogen produce zero tailpipe emissions, however the WTW CO_2 benefit depends on how the H_2 was produced
- **Costs:** Altough costs are reducing, a FC bus still costs 3-6 times more than the price for a conventional bus

Powertrain



Safety and Limitations

- ✓ Hydrogen fuel cell powered buses have been safely demonstrated in several cities throughout the world
- ⛔ The lack of hydrogen infrastructure limits current use to fleets that regularly return to a depot
- ⛔ Staff training would be required to ensure safe handling of the hydrogen fuel and fuel cell system

Technology Applicability

- Fuel cell technology has successfully been demonstrated in city buses
- At least one European developer plans to market a fuel cell hybrid 7.5 tonne truck, however since production volumes will initially be low, this will be a niche product

Visualisation

Picture: Transport for London, Hydrogen Bus

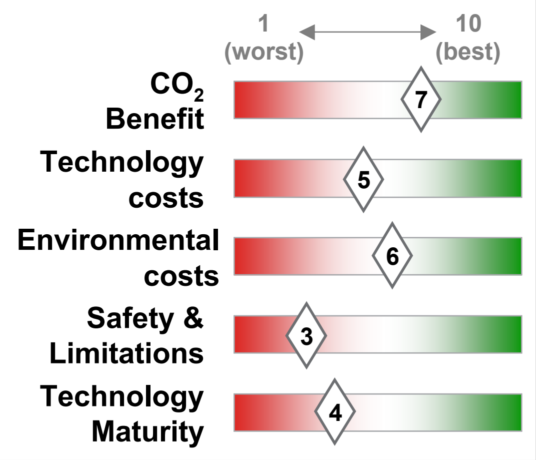
Source: Ricardo Analysis; Roads2HyCom (Ricardo); Element Energy – Full sources available on detail slides in the attached annex

Another application for fuel cell technology on heavy-duty trucks is auxiliary power units for managing hotel loads

Fuel Cell APUs

- **Concept:** Fuel cell auxiliary power unit (APU) to supply electricity for hotel loads in long-haul heavy duty trucks while stationary, instead of idling the main engine
- **Base Functioning:** The FC APU system provides electricity for the on-board hotel loads such as cabin heating and cooling, computer, GPS equipment, and electricial applicances
- **CO_2 Benefit:** It is expected that this technology will offer a CO_2 benefit due to reduced fuel consumption, but since the technology is still under development the actual CO_2 benefit has not yet been published
- **Costs:** Once ready for market, it is expected that FC APU systems will have a payback period of < 2 years in terms of fuel saved

Powertrain



Safety and Limitations

- ✓ Fuel reformers are currently being developed so that fuel cell APUs can be run on conventional fuels such as diesel or biodiesel
- ⛔ A new technology will require an appropriate certification process to prove it is safe to use
- ⛔ Currently, fuel cell APU products for trucks are being developed for the North American market, not the European market

Technology Applicability

- Fuel cell APUs offer an alternative to idling the main engine when the vehicle is stationary. This would lead to significant fuel savings and corresponding reduction in tailpipe emissions
- This technology is particularly applicable to long-haul trucks which require electricity to run hotel type loads while stationary

Visualisation

Picture: Ricardo

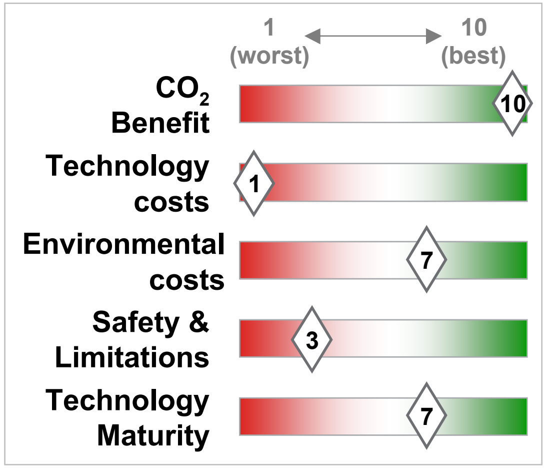
Source: Ricardo Analysis; Roads2HyCom (Ricardo) – Full sources available on detail slides in the attached annex

Electric commercial vehicles are available with a GVW up to 12t and benefit from lower running costs and taxes

Electric Vehicles

- **Concept:** Vehicle which is driven by a battery powered electric motor
- **Base Functioning:** 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
- **CO_2 Benefit:** Tailpipe CO_2 emissions are 0g/km and overall emissions are estimated to be 40% lower than conventional diesel, but this is dependent on fuel source used to generate electricity
- **Costs:** Smiths Newton electric 7.5t vehicle (very similar to medium duty benchmark) is between £78,387 and £80,886
- **Environmental Benefit:** Electric vehicles have societal benefits in that they reduce road noise

Powertrain



Safety and Limitations

- ✓ Less stressful driving
- ✓ Lower mainteneance and servicing requirements
- ⛔ Lower vehicle payload than comparable diesel vehicle
- ⛔ Limited to GVW of 12t
- ⛔ Low residual vehicle values
- ⛔ Operation limited to central depot based fleets
- ⛔ Reduction in road noise needs to be handled carefully to ensure no adverse effects for vulnerable road users

Technology Applicability

- Limited to vehicles up to 12t
- Best suited to vehicles operating from a single depot and with daily mileage of <100miles
- Greatest benefit for urban applications where exemption from congestion charge and low emission and noise operation is beneficial

Visualisation

Picture: Smith Newton from sev-us.com

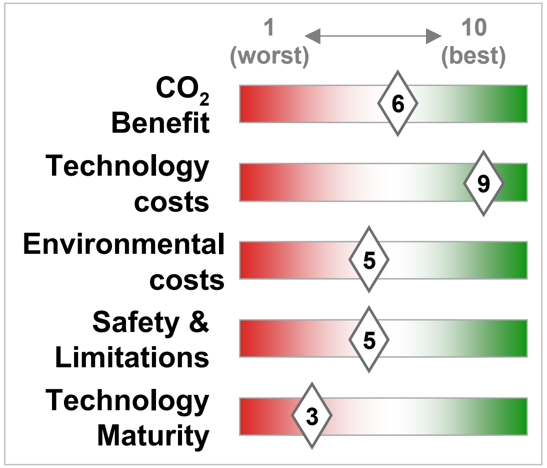
Source: Smiths Electric Vehicles; The Benefits of Operating an Electric Vehicle in an Urban Environment, Freight Best Practice, April 2009 – Full sources available on detail slides in the attached annex

Stop / Start mild hybrids offer best CO_2 benefit for frequent stop / start applications and are currently only found on light vehicles

Hybrid Powertrains – Stop / Start Mild Hybrid

- **Concept:** Stop the engine running whenever the vehicle is stationary
- **Base Functioning:** System uses a high-voltage e-motor mounted to the crankshaft to operate stop / start, along with regenerative braking
- **CO_2 Benefit:** 0 – 30%, averaging around 6%, but very dependent on duty cycle. Duty cycle with frequent stop / start will obtain greatest benefit
- **Costs:** £545 as option for Mercedes Sprinter, likely to be more for larger vehicles

Powertrain



Safety and Limitations

- ✓ Simple solution which has no high voltage safety hazards
- ⛔ Not suitable for vehicle bodies which are engine powered when vehicle is stationary
- ⛔ Only suitable for urban applications with frequent stop/start

Technology Applicability

- Greatest CO_2 reduction potential for vehicles operating over an urban duty cycle

Visualisation

Picture: Ricardo HyTrans

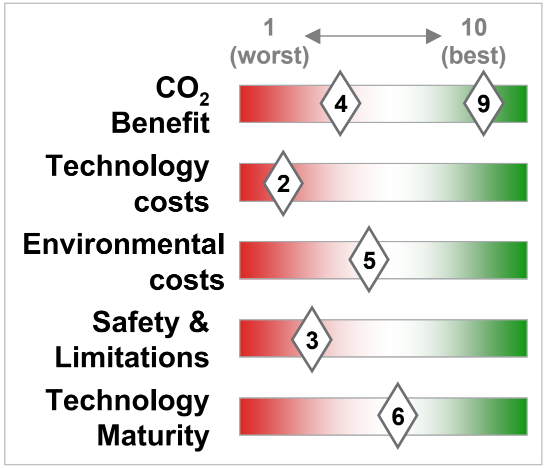
Source: Ricardo – Full sources available on detail slides in the attached annex

Hybrid Vehicles provide high potential CO_2 reduction for urban applications but are expensive and will require maintenance training

Hybrid Powertrains – Full Hybrid

- **Concept:** A powertrain which can use more than one fuel source to provide energy to propel the vehicle
- **Base Functioning:** Typically implemented as hybrid electric vehicles where electrical energy is stored in batteries which can be used to drive an electric motor to power the vehicle or supplement engine power
- **CO_2 Benefit:** Ranges significantly dependent upon vehicle operation but averages 20% for medium (urban) and 7% for heavy duty (long haul) applications
- **Costs:** Significant technology on cost of additional hybrid components. Some environmental impact in terms of battery manufacture and disposal

Powertrain



Safety and Limitations

- ✓ Lower brake wear due to use of regenerative braking – leads to lower maintenance costs
- ✓ Makes use of existing fuel infrastructure
- ✓ Vehicles have better acceleration
- ⛔ Some vehicles have a reduction in payload
- ⛔ Engine stop/start unsuitable for some applications
- ⛔ Requires training of maintenance staff to safely work with high voltage systems

Technology Applicability

- Greatest CO_2 reduction potential for vehicles operating over an urban duty cycle
- CO_2 savings still possible for long haul applications but business case requires more consideration

Visualisation

Picture: DAF LF Hybrid

Source: OEM corporate websites and press releases – Full sources available on detail slides in the attached annex

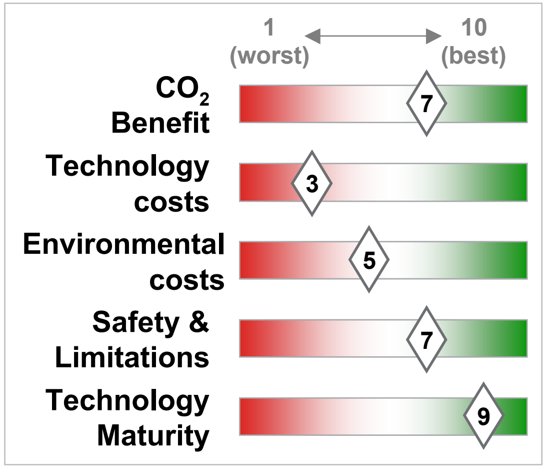
Contents

AMTs is a mature technology which offers good CO_2 reduction potential by keeping the engine in its optimum speed band

Transmissions

- **Concept:** Replacement of manual transmissions with automated variants
- **Base Functioning:** Automated transmission based on a manual (AMT) which has similar mechanical efficiency to a manual transmission but automated gear shifts to optimise engine speed
- **CO_2 Benefit:** 7 – 10% benefit replacing a manual with AMT
- **Costs:** Additional cost of £1,000 - £1,500 for an AMT over a manual

Powertrain



Safety and Limitations

- ✓ Optimum protection against external influences
- ✓ Increased service intervals
- ✓ Fast gearshifts which save fuel
- ✓ Extended clutch service life
- ✓ No limitations on vehicle usage
- ✓ No additional safety issues
- ⛔ Shift quality is not as smooth as a torque converter automatic

Technology Applicability

- AMT technology is applicable to both medium and heavy duty applictions, offering good CO_2 benefits over both urban and highway duty cycles
- DCT technology is not applicable to heavy duty and not applicable to UK medium duty market as it would result in a CO_2 penalty

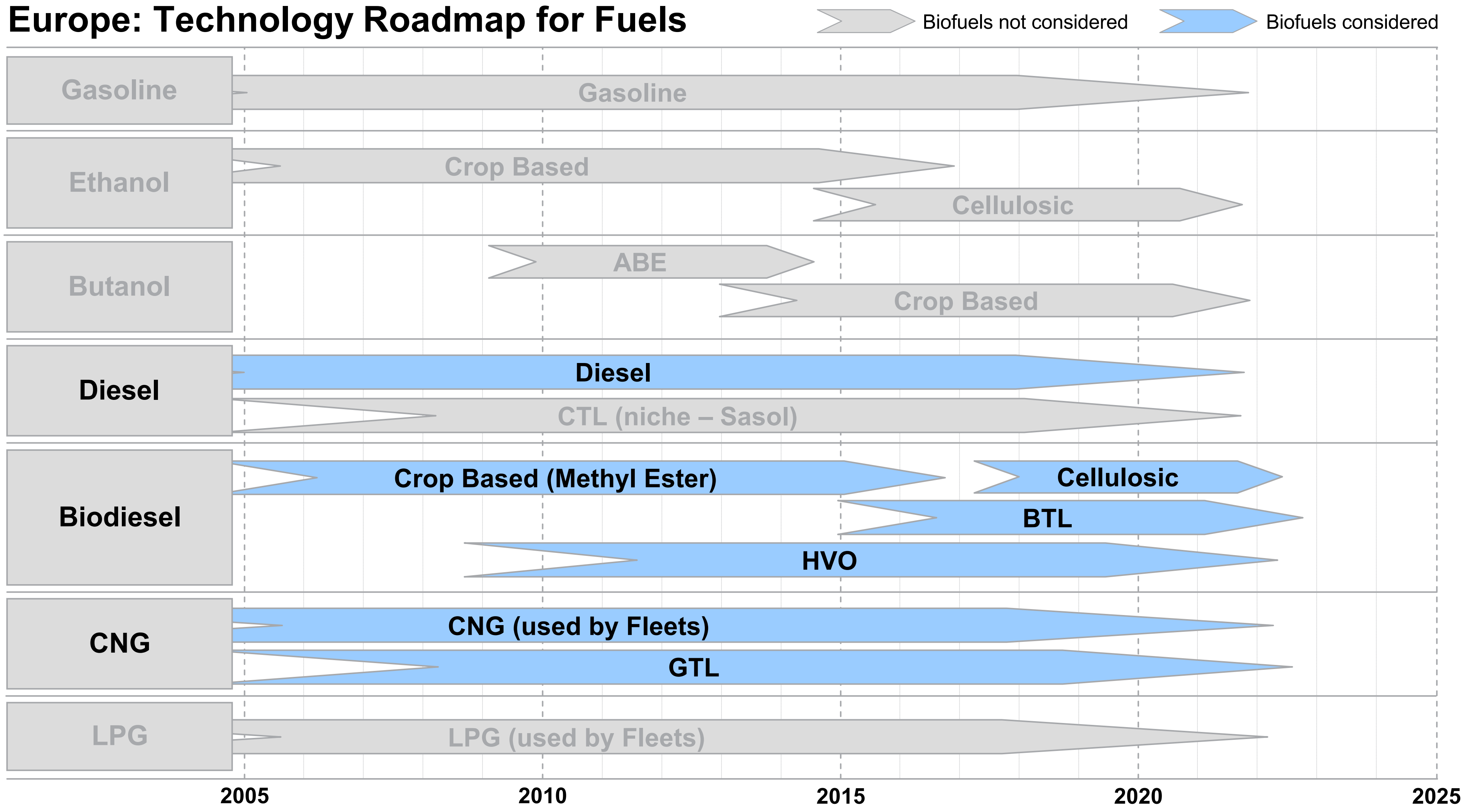
Visualisation

Picture: ZF AS-Tronic AMT Family (www.zd.com)

Source: Ricardo Research and Analysis – Full sources available on detail slides in the attached annex

Contents

The roadmap for future fuels shows a diversification of fuels used for heavy duty on-highway applications

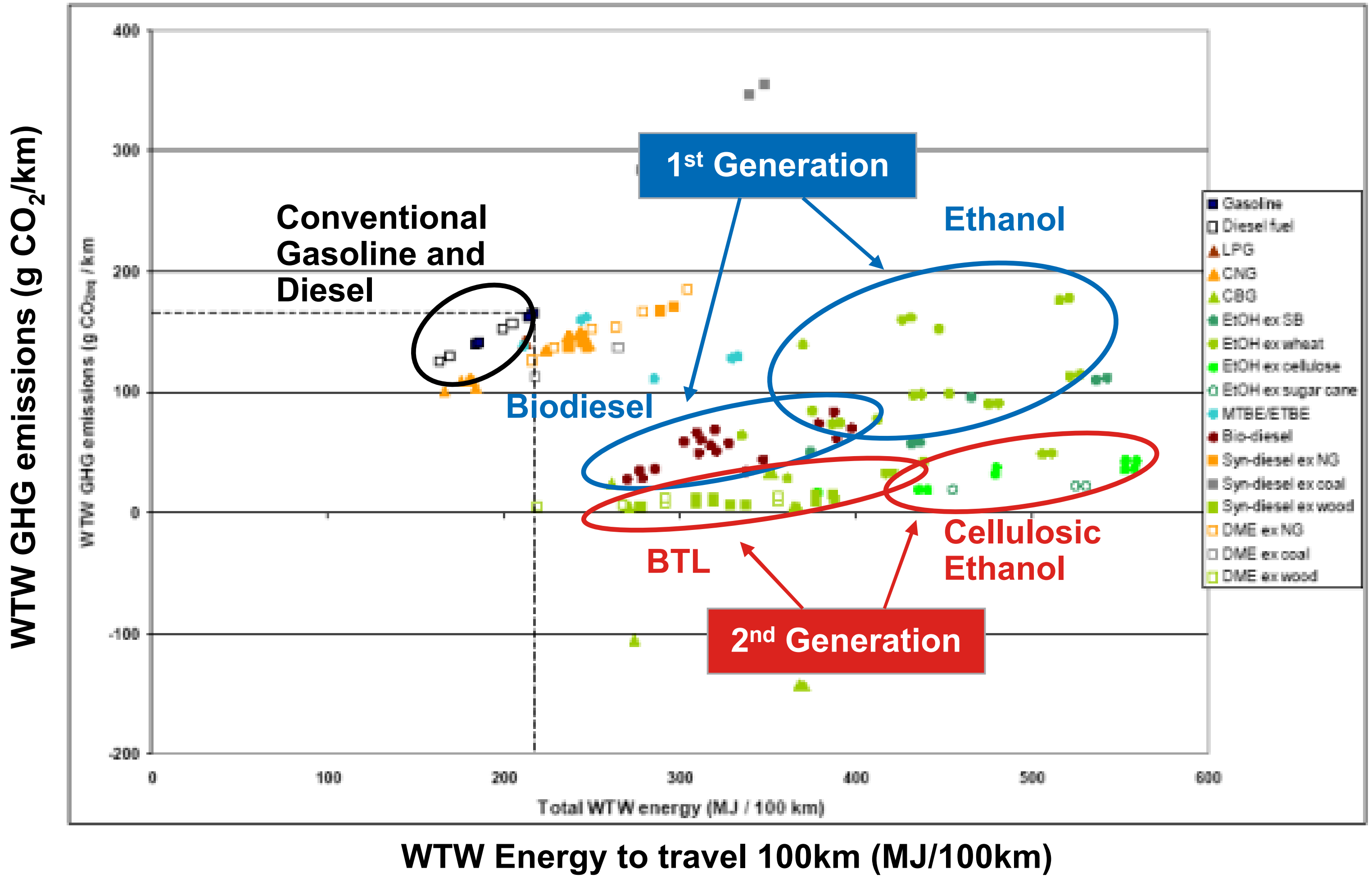


Europe: Technology Roadmap for Fuels

Source: Ricardo Analysis

Not all biofuels are equal in terms of WTW Energy and GHG emissions savings

WTW Energy Requirement and GHG Emissions



WTW – Well to Wheels
GHG – Greenhouse Gas

Source: Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context - EUCAR, CONCAWE and JRC

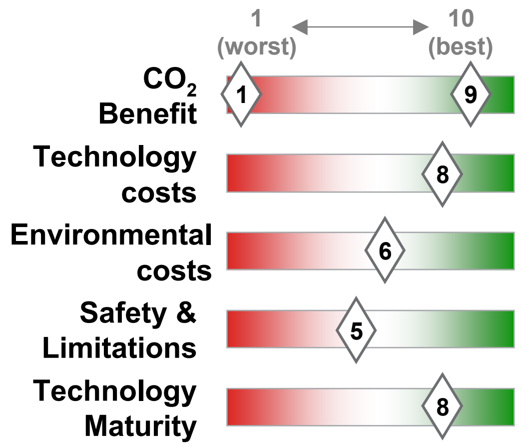
Contents

FAME is a 1st generation biodiesel with the potential to reduce WTW GHG emissions

FAME

- **Concept:** 1st generation biodiesel derived from vegetable oils or animal fats and alcohols
- **Base Functioning:** FAME can be blended with conventional diesel to power engines. For higher blend ratios some modifications to the engine may be required
- **CO_2 Benefit:** Needs to be considered on WTW basis and depends on feedstock, country of origin and production process. In UK, potential GHG reduction ranges from –5 to 90%
- **Costs:** FAME is thought to be economically viable if oil is 80-100 $/barrel

Fuel Technology



Safety and Limitations

- ✓ FAME has completed the health effects testing requirements of the 1990 CAA
- ✓ The use of biodiesel as a transport fuel does not require changes to the refuelling infrastructure
- ⛔ FAME contains less energy per litre than conventional diesel
- ⛔ Bio content as low as 5% can cause significant injection system deposits
- ⛔ Low temperatures can cause waxing, clogged lines and filters

Technology Applicability

- FAME (1st Generation Biodiesel) is available, although quality varies due to the range of feed stocks and manufacturing processes
- FAME can blended with conventional diesel to be used to fuel diesel engines, however there may be warranty issues if the blend is high

Visualisation

Picture:

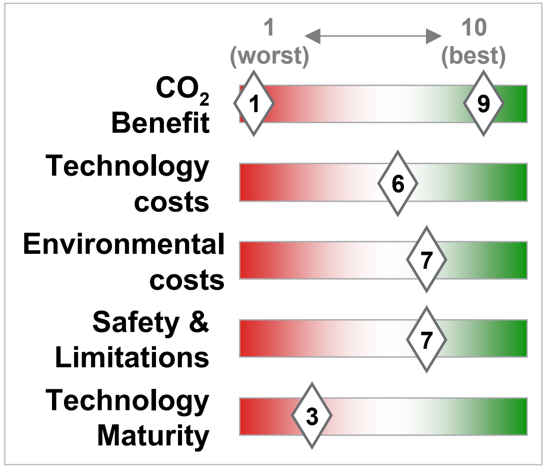
Source: Ricardo Analysis – Full sources available on detail slides in the attached annex

BTL is a 2nd generation biodiesel that can be produced to waste, thus leading to GHG reductions

BTL

- **Concept:** 2nd generation biodiesel produced by converting Biomass to Liquid (BTL)
- **Base Functioning:** BTL can be run in any diesel engine
- **CO_2 Benefit:** 60-90% on WTW basis, depending on production scenario
- **Costs:** Expected to be more expensive than 1st generation biodiesel since the production process is more energy intensive

Fuel Technology



Safety and Limitations

- ✓ BTL has potentially better fuel characteristics (effectively synthetic diesel)
- ✓ BTL can be used without any adjustment to existing infrastructure or engine systems,
- ⛔ However this relatively new fuel needs to be proven on an industrial scale

Technology Applicability

- Since BTL is a synthetic diesel, it will be possible to use it to fuel all diesel vehicle without modification
- BTL is not currently commercially available, although a beta-test production plant is under construction in Germany

Visualisation

Picture: Choren

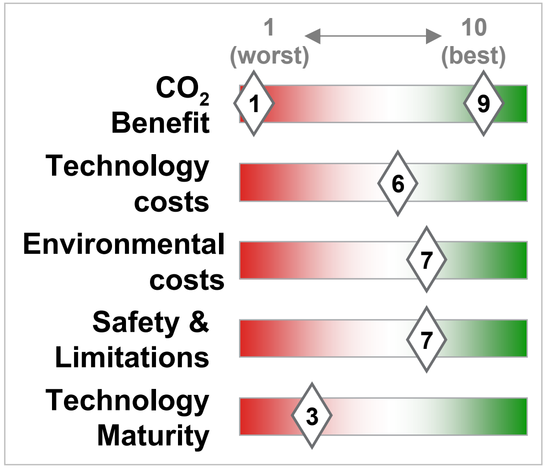
Source: Ricardo Analysis, Choren, available at: www.choren.com – Full sources available on detail slides in the attached annex

HVO is a 2nd generation biodiesel made by hydro-treating vegetable oils

HVO

- **Concept:** 2nd generation biodiesel made by treating vegetable oil or animal fat with hydrogen
- **Base Functioning:** HVO can be used to fuel any conventional diesel vehicle
- **CO_2 Benefit:** 40-60% WTW GHG reductions compared to conventional diesel
- **Costs:** It is expected that HVO will be more expensive than 1st generation biodiesel

Fuel Technology



Safety and Limitations

- ✓ HVO has potentially better fuel characteristics (effectively synthetic diesel)
- ✓ HVO can be used without any adjustment to existing infrastructure or engine systems
- ⊖ However, HVO is a relatively new fuel and is not yet been prove on an industrial scale

Technology Applicability

- HVO can potentially be used to fuel any diesel vehicle
- HVO is commercially available in Finland, as a 10% blend in Neste Oil‘s Green Diesel

Visualisation

Picture: Neste Oil

Source: Ricardo Research and Analysis – Full sources available on detail slides in the attached annex

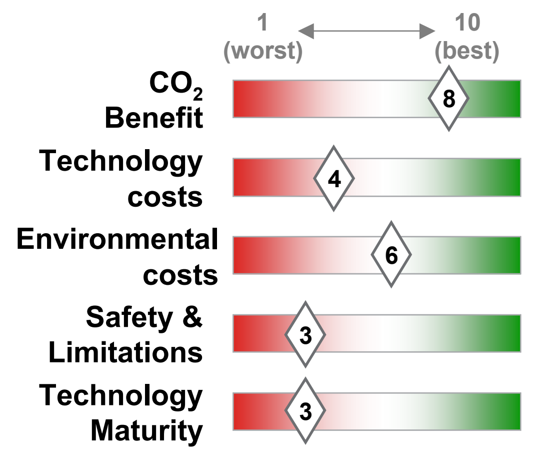
Contents

Running heavy-duty engines on CNG could have a 10-15% CO_2 benefit, but lack of infrastructure restricts use to fleets

CNG

- **Concept:** Spark ignited CNG variants on base diesel engines
- **Base Functioning:** Injection of gas into intake and combustion initiated with spark
- **CO_2 Benefit:** 10-15%
- **Costs:** Low volume production means the retail price for CNG engines is 20-25% higher than the equivalent diesel engine
- Several OEMs are developing CNG engines, although these tend to be for fleet applications such as buses and refuse trucks rather than HGVs

Fuel Technology



Safety and Limitations

- ✓ CNG has been used safely in many automotive applications worldwide
- ✓ CNG engines are most appropriate to urban fleets, such as buses
- ⊖ Public access to the CNG refuelling infrastructure is currently limited
- ⊖ CNG leaks can cause explosions and fire

Technology Applicability

- Buses
- Trucks
- Stationary engines

Visualisation

Picture:

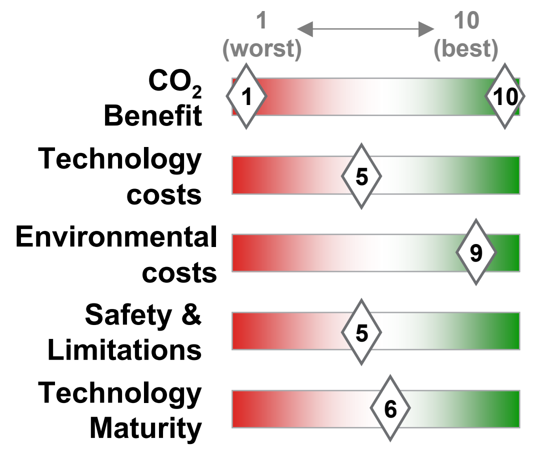
Source: Ricardo Analysis – Full sources available on detail slides in the attached annex

Biogas can be used to power vehicles is a similar way as CNG, with a similar price and less impact on the environment

Biogas

- **Concept:** Upgraded biogas, made from organic material, used to fuel vehicles
- **Base Functioning:** Biogas upgraded to 95% methane can be used instead of natural gas to power engines. Like CNG engine, the gas is injection of gas into intake and combustion initiated with spark
- **CO_2 Benefit:** Current studies claim 60% CO_2 benefit when compared to diesel vehicle but varies with process
- **Costs:** A new biogas heavy goods vehicles could be around £25,000 to £35,000 more expensive, whilst new biogas vans cost approximately £4,000 to £5,000 more.

Fuel Technology



Safety and Limitations

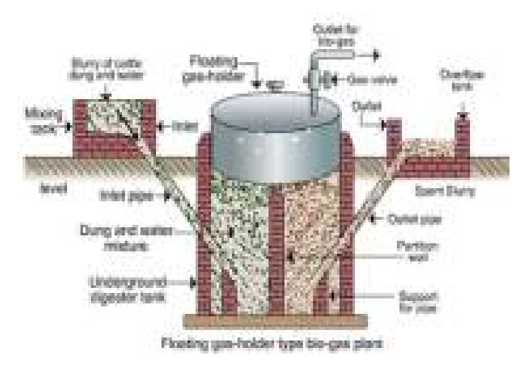
✓ Biogas can be used safely to fuel any vehicle, following the same precautions followed for natural gas fuelled vehicles

⛔ The uptake of biogas as a road fuel requires the development of a national production and distribution infrastructure

Technology Applicability

- Upgraded biogas (95% content methane) could be used in any vehicle designed to run on natural gas

Visualisation



Picture:

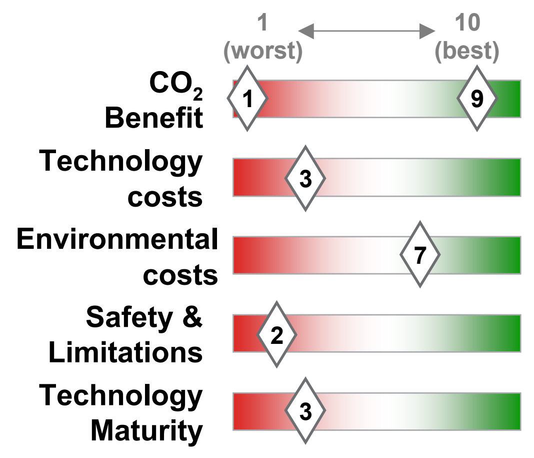
Source: Ricardo Analysis; Energy Savings Trust; www.nfuonline.com; – Full sources available on detail slides in the attached annex

Hydrogen can be used to fuel vehicles, but this also requires the development of a national hydrogen refuelling infrastructure

Hydrogen

- **Concept:** A spark-ignition internal combustion engine run on hydrogen to reduce engine-out emissions
- **Base Functioning:** A gas engine can be converted to run on hydrogen with minor modifications
- **CO_2 Benefit:** Running an engine on hydrogen produces neglible CO_2 emissions, however the WTW benefit depends on the energy source and method used to produce the hydrogen
- **Costs:** It is expected that a H_2-ICE would be a priced similar to a gas ICE. However costs of the on-board hydrogen storage tank would be significantly higher since the hydrogen would need to be stored at a higher pressure (350-700 bar)

Fuel Technology



Safety and Limitations

- ✓ Numerous demonstration projects have shown the hydrogen can safely be used to fuel vehicles
- ⛔ The current lack of infrastructure for refuelling hydrogen vehicles limits the uptake and use of H_2-ICE technology

Technology Applicability

- No OEMs are currently considering developing H_2-ICEs for HVGs
- However, over the past decade there have been numerous high profile fleet trials of H_2-ICE buses (e.g. HyFLEET:CUTE project)

Visualisation

Picture: PLANET

Source: Ricardo Analysis – Full sources available on detail slides in the attached annex

Contents

The technologies considered in the feasibility analysis have been ranked according to CO_2 reduction potential and commercial timing

- Over the following 6 slides the technologies considered in the feasibility analysis have been ranked according to CO_2 reduction potential and maturity, i.e. time to market
- Benefits and costs are as scored in the feasibility analysis with the greater the number of blue dots, the more attractive the technology

  ●●●●●●●●●○
  ●●●●○○○○○○
  ●●○○○○○○○○
  ↑ Increasingly attractive

- For technologies where there is a range of benefits or costs, the range is indicated by a change from dark to mid blue dots, with the dark blue indicating the start of the range and the light blue the end, e.g. benefit / cost ranging from 4 to 9 would be shown as: ●●●●◍◍◍◍◍○

  Start End

- For applicability of heavy duty (HD), assumed to be long haul applications, and medium duty (MD), assumed to be urban applications, the following rating has been applied:
  - ⛔ No benefit / applicability
  - ✓ Lower benefit / applicability
  - ✓✓ Maximum benefit / applicability
- Technology timeframe is determined by the technology maturity level and assumes that the technology will be mass market within the following timeframes:
  - Near Term <5 year, technology maturity 6+
  - Medium Term 5 – 10 years, technology maturity (3 – 5)
  - Long Term > 10 years, technology maturity (1 & 2)

Near term vehicle technologies that offer greatest CO$_2$ reduction potential are electric bodies and aerodynamic trailers

Low Carbon Technologies for HGVs – Vehicle

Technology	CO$_2$ Benefit	Technology and Environmental Costs		Safety and Limitations	HGV Applicability	
Electric Bodies	●●●●●●●●●○	Econ.	●●●●●◍◍◍◍◍	●●●●○○○○○○	MD	✓ ✓
		Env.	●●●●●●○○○○		HD	✓ ✓
Aerodynamic Trailers	●●●●●●●●●○	Econ.	●●●●○○○○○○	●●●●●●○○○○	MD	✓
		Env.	●●●●●●○○○○		HD	✓ ✓
SAFED Driver Training	●●●●●●●●○○	Econ.	●●●●●●●●●○	●●●●●●●●●○	MD	✓ ✓
		Env.	●●●●●○○○○○		HD	✓ ✓
Single Wide Tyres	●●●●●●○○○○	Econ.	●●●●●●●●●●	●●●●●○○○○○	MD	⛔
		Env.	●●●●●●●●○○		HD	✓ ✓
Automatic Tyre Pressure Adjustment	●●●●●●○○○○	Econ.	●●●●●○○○○○	●●●●●●●○○○	MD	✓
		Env.	●●●●●○○○○○		HD	✓ ✓
Low Rolling Resistance Tyres	●●●●●○○○○○	Econ.	●●●●●●●●●●	●●●●●●●○○○	MD	⛔
		Env.	●●●●○○○○○○		HD	✓ ✓
Aerodynamic Fairings	●●●●◍◍○○○○	Econ.	●●●●●●●●●○	●●●●●●○○○○	MD	✓
		Env.	●●●●○○○○○○		HD	✓ ✓
Spray Reduction Mud Flaps	●●●●○○○○○○	Econ.	●●●●●●●○○○	●●●●●●●●●○	MD	⛔
		Env.	●●●●●○○○○○		HD	✓ ✓
Predictive Cruise Control	●●●●○○○○○○	Econ.	●●●●●●●●●○	●●●●●●○○○○	MD	⛔
		Env.	●●●●●○○○○○		HD	✓ ✓

Source: All ratings are based on the subjective ratings of Ricardo engineers. These ratings should therefore be used as direction input/guideline only.

For powertrain technologies alternative powertrains of electric vehicle and full hybrids offer the best potential in the near term

Low Carbon Technologies for HGVs – Powertrain

Technology	CO$_2$ Benefit	Technology and Environmental Costs	Safety and Limitations	HGV Applicability
Electric Vehicles	●●●●●●●●●●	Econ. ●○○○○○○○○○ Env. ●●●●●●●○○○	●●●○○○○○○○	MD ✓ HD ⛔ Limited GVW
Full Hybrid	●●●●◐◐◐◐◐○	Econ. ●●○○○○○○○○ Env. ●●●●●○○○○○	●●●○○○○○○○	MD ✓ ✓ HD ✓
Automated Transmissions	●●●●●●●○○○	Econ. ●●●○○○○○○○ Env. ●●●●●○○○○○	●●●●●●●○○○	MD ✓ ✓ HD ✓ ✓
Air Compressor	●●●○○○○○○○	Econ. ●●●●●●●●●○ Env. ●●●●●●○○○○	●●●●○○○○○○	MD ✓ HD ✓ ✓
Electric / Variable flow oil Pumps	●●●○○○○○○○	Econ. ●●●●●●●●●○ Env. ●●●●●○○○○○	●●●●○○○○○○	MD ✓ ✓ HD ✓ ✓
Mechanical Turbocompound	●●●○○○○○○○	Econ. ●●●●●●●○○○ Env. ●●●●○○○○○○	●●●●○○○○○○	MD ✓ HD ✓ ✓
Combustion Systems	●●●○○○○○○○	Econ. ●●●●●○○○○○ Env. ●●●●●●●●●○	●●●●●●○○○○	MD ✓ ✓ HD ✓ ✓
Engine Friction	●●○○○○○○○○	Econ. ●●●●●●●●●○ Env. ●●●●●●○○○○	●●●●●○○○○○	MD ✓ ✓ HD ✓ ✓

Source: All ratings are based on the subjective ratings of Ricardo engineers. These ratings should therefore be used as direction input/guideline only.

Despite sustainability concerns associated with indirect effects of biofuels, first generation biofuels and biogas offer the greatest CO_2 benefit in the near term

Low Carbon Technologies for HGVs – Fuels

Technology	CO_2 Benefit	Technology and Environmental Costs		Safety and Limitations	HGV Applicability		
Biogas	●◍◍◍◍◍◍◍◍◍	Econ.	●●●●●○○○○○	●●●●●○○○○○	MD	✓ ✓	Limited availability
		Env.	●●●●●●●●●○		HD	✓	
FAME	●◍◍◍◍◍◍◍◍○	Econ.	●●●●●●●●○○	●●●●●○○○○○	MD	✓ ✓	
		Env.	●●●●●●○○○○		HD	✓ ✓	

Source: All ratings are based on the subjective ratings of Ricardo engineers. These ratings should therefore be used as direction input/guideline only.

Medium term powertrain technologies with greatest CO_2 reduction potential are fuel cell APUs, stop/start hybrid systems and heat exchangers

Low Carbon Technologies for HGVs – Powertrain

Technology	CO_2 Benefit	Technology and Environmental Costs		Safety and Limitations	HGV Applicability	
Fuel Cell APU	●●●●●●●○○○	Econ.	●●●●●○○○○○	●●●○○○○○○○	MD	⛔
		Env.	●●●●●●○○○○		HD	✓ ✓
Stop / Start Hybrid	●●●●●●○○○○	Econ.	●●●●●●●●●○	●●●●●○○○○○	MD	✓ ✓
		Env.	●●●●●○○○○○		HD	⛔
Waste Heat Recovery – Heat Exchanger	●●●●○○○○○○	Econ.	●●●●○○○○○○	●●●●○○○○○○	MD	✓ ✓
		Env.	●●●●○○○○○○		HD	✓ ✓
Pneumatic Booster System	●●●○○○○○○○	Econ.	●●●●●●●●●○	●●●●●○○○○○	MD	✓ ✓
		Env.	●●●●●●○○○○		HD	✓
Electric / Variable flow water pump	●●●○○○○○○○	Econ.	●●●●●●●●●○	●●●●●○○○○○	MD	✓
		Env.	●●●●●●○○○○		HD	✓ ✓
Electric Turbocompound	●●●○○○○○○○	Econ.	●●●●○○○○○○	●●●●○○○○○○	MD	✓
		Env.	●●●●○○○○○○		HD	✓ ✓
Gas Exchange Improvement	●●○○○○○○○○	Econ.	●●●●●●○○○○	●●●○○○○○○○	MD	✓
		Env.	●●●●●●○○○○		HD	✓

Source: All ratings are based on the subjective ratings of Ricardo engineers. These ratings should therefore be used as direction input/guideline only.

Fuel technologies for the medium term include BTL, HVO, Hydrogen and CNG of which CNG offers the lowest CO_2 reduction

Low Carbon Technologies for HGVs – Fuels

Technology	CO_2 Benefit	Technology and Environmental Costs		Safety and Limitations	HGV Applicability	
BTL	●◉◉◉◉◉◉◉◉○	Econ.	●●●●●●○○○○	●●●●●●●○○○	MD	✓ ✓
		Env.	●●●●●●●○○○		HD	✓ ✓
HVO	●◉◉◉◉◉◉◉◉○	Econ.	●●●●●●○○○○	●●●●●●●○○○	MD	✓ ✓
		Env.	●●●●●●●○○○		HD	✓ ✓
Hydrogen	●◉◉◉◉◉◉◉◉○	Econ.	●●●○○○○○○○	●●○○○○○○○○	MD	⛔
		Env.	●●●●●●●○○○		HD	⛔
CNG	●●●●●●●●○○	Econ.	●●●●○○○○○○	●●●○○○○○○○	MD	✓ ✓
		Env.	●●●●●●○○○○		HD	✓

Source: All ratings are based on the subjective ratings of Ricardo engineers. These ratings should therefore be used as direction input/guideline only.

Long term technologies of vehicle platooning and fuel cells have good CO_2 reduction potential but also commercial challenges

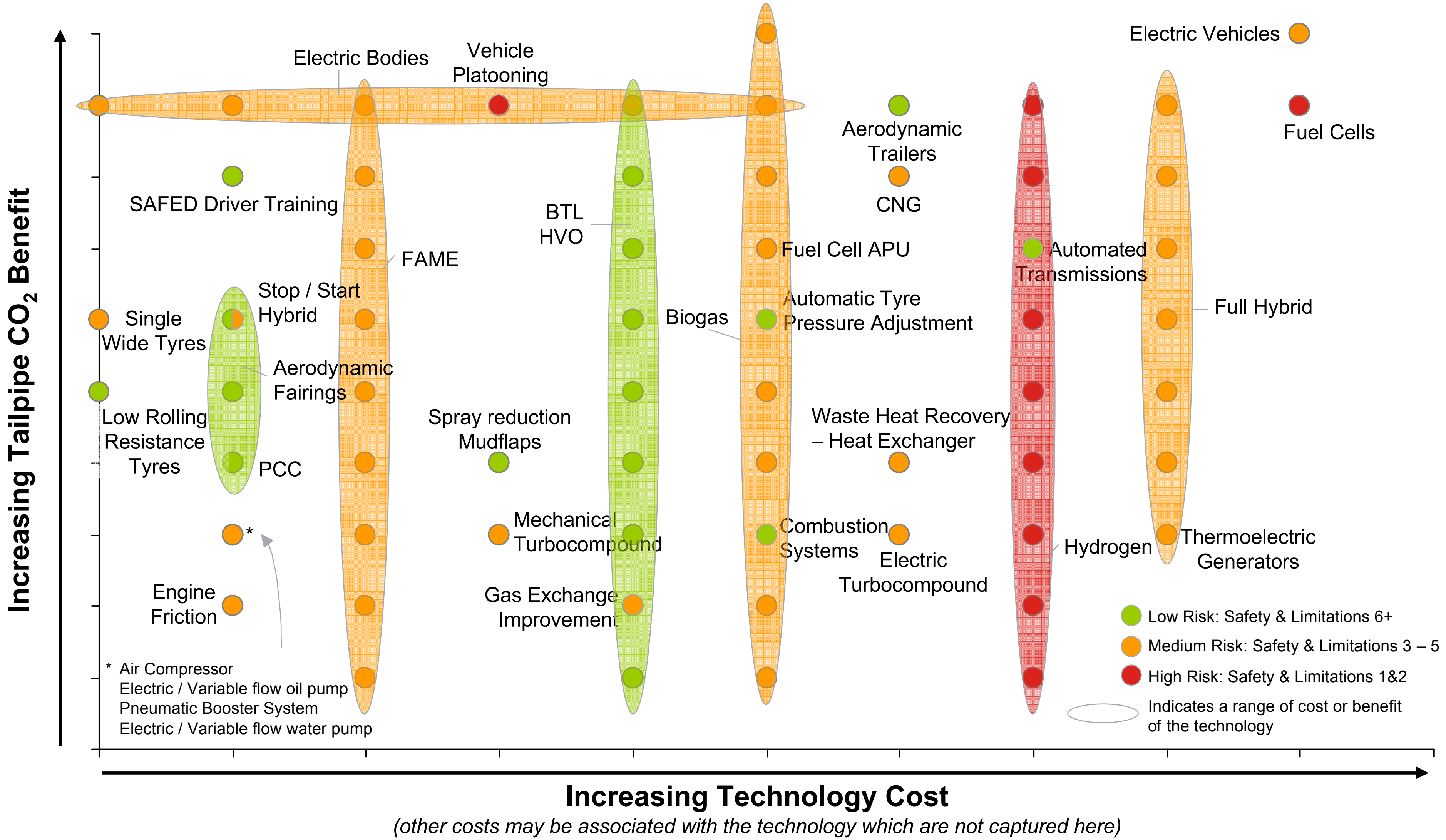
Low Carbon Technologies for HGVs – Vehicle and Powertrain

Technology	CO_2 Benefit	Technology and Environmental Costs		Safety and Limitations	HGV Applicability	
Vehicle Platooning	●●●●●●●●●○	Econ.	●●●●●●●○○○	●●○○○○○○○○	MD	⛔
		Env.	●●●●●●○○○○		HD	✓ ✓
Fuel Cells	●●●●●●●●●○	Econ.	●○○○○○○○○○	●●○○○○○○○○	MD	✓
		Env.	●●●●●●○○○○		HD	⛔
Thermoelectric Generators	●●●○○○○○○○	Econ.	●●○○○○○○○○	●●●●○○○○○○	MD	✓
		Env.	●●●●○○○○○○		HD	✓ ✓

Source: All ratings are based on the subjective ratings of Ricardo engineers. These ratings should therefore be used as direction input/guideline only.

Implementation of many of the low carbon technologies present a certain degree of risk, which can be better understood through trials

Cost vs. Benefit of Low Carbon Technologies



* Air Compressor
Electric / Variable flow oil pump
Pneumatic Booster System
Electric / Variable flow water pump

(other costs may be associated with the technology which are not captured here)

Aerodynamic trailers, electric bodies & vehicle platooning offer the most promising CO_2 reduction potential for vehicle technologies

- The technologies with the greatest CO_2 reduction potential for the vehicle area are:
  - **Aerodynamic trailers: CO_2 Benefit – 9**
    - Large benefits in CO_2 emissions and fuel consumption reduction for fleets using the teardrop trailers for articulated vehicles in real world situations
    - Technology currently is limited to articulated trailers and greatest benefit will be from fleets with high average speeds and mileage
  - **Electric Bodies: CO_2 Benefit – 9**
    - Electrification of the power requirements of vehicle bodies such as refrigeration and refuse offers significant potential for CO_2 reduction, however this is limited to specific body types which are a small portion of the overall market
  - **Vehicle Platooning: CO_2 Benefit – 9**
    - Close but safe operation of HGVs on motorways has significant CO_2 reduction potential not only for following vehicles but also for the lead vehicle
    - In addition the lead vehicle may earn revenue from allowing others to form a platoon behind it
    - However there are a number of safety and implementation challenges to address before this is likely to become reality
  - **SAFED Driver Training: CO_2 Benefit – 8**
    - Good CO_2 potential from initial case studies, but it yet to be seen how long the effects last
    - Benefit varies widely from driver to driver

Powertrain technologies electric vehicles, fuel cells and full hybrids offer greatest tailpipe CO_2 reduction but not without limitations

- The technologies with the greatest CO_2 reduction potential for the powertrain area are:
  - **Electric Vehicles: CO_2 Benefit – 10**
    - 100% reduction in tailpipe CO_2 emissions, however lifecycle CO_2 benefit is likely to be considerably less
    - Limited currently to applications with maximum GVW of 12t
    - Require central depot for overnight charging with current levels of infrastructure for electric vehicle charging
    - Requirement to be run from a central depot may limit resale and hence affect resale value
  - **Fuel Cells: CO_2 Benefit – 9**
    - Replacement of internal combustion engine with a fuel cell results in 100% reduction in tailpipe CO_2 emissions if it is run on hydrogen
    - Limitations with the hydrogen infrastructure for refuelling and for storage of the fuel on-board the vehicle without affecting payload and cargo space
  - **Full Hybrid: CO_2 Benefit – 4 – 9**
    - Tailpipe CO_2 emissions reduction can be as high as 30%, but this is very dependent on vehicle duty cycle
    - For applications where the vehicle operates in a frequent stop/start mode hybrids have greatest CO_2 reduction potential. Full hybrids also have the benefit of entering city centres which have restrictions on emissions
    - For long haul applications, CO_2 benefit is lower, but can be around 5%
    - Additional weight of hybrid system is not always off-set by a reduction in engine capacity and can lower vehicle payload

Fuel technologies with greatest lifecycle CO_2 benefit are biogas, biofuels and hydrogen, however tailpipe reductions are lower

- The technologies with the greatest CO_2 reduction potential for the fuel area are:
  - **Biogas: CO_2 Benefit – 10**
    - As a gas used in an internal combustion engine, tailpipe CO_2 reduction is similar to that of CNG
    - However if well to wheel analysis is considered, the overall CO_2 benefit of biogas is considerably higher as use is being made of a waste gas which has greater greenhouse harm potential than CO_2
  - **Biofuel: CO_2 Benefit – 9**
    - Tailpipe CO_2 emissions from biofuels (FAME, BTL and HVO) are similar to that of fossil diesel
    - Well to wheel analysis of CO_2 emissions produces a wide range of values depending on the feedstock used and the process used to manufacture the fuel
    - OEMs do not always warrant the use of fuels with high concentration of biodiesel as it can foul the fuel injection system
  - **Hydrogen: CO_2 Benefit – 9**
    - Tailpipe CO_2 emissions are near zero as hydrogen is a non-carbon fuel so only emissions come from burning of oil
    - Well to wheel CO_2 benefit of hydrogen is also dependent on how the hydrogen is made, with some methods resulting in higher lifecycle CO_2 emissions than diesel
    - Storage of the fuel on-board the vehicle is also an issue without reducing vehicle payload and cargo space
    - Further the refuelling infrastructure for hydrogen does not yet exist and as such would only suit vehicle fleets operating from a central depot

Technologies whose CO_2 benefit does not vary greatly for a given application due to external influences can act as potential indicative guide

- While some technologies offer greater potential CO_2 reduction than others, these are not necessarily the best technologies to use as a basis for CO_2 reduction as the benefits they offer can vary significantly based on external influences such as:
  - Driving style
  - Route characteristics
  - Vehicle maintenance and accessories
- An indicative guide means, if a particular technology is applied to a particular vehicle type, the CO_2 benefits are consistent, repeatable and not significantly affected by these variables, such that statistics about take-up of a particular technology can be translated into an estimated fleet CO_2 saving
  - Example:
    - Aerodynamic trailers are a good indicative guide, their CO_2 saving performance is consistent and repeatable when applied to heavy duty articulated vehicles used on a constant high speed duty cycle
    - Full hybrids are a poor indicative guide, as their CO_2 improvement benefit is highly dependent on duty cycle, vehicle architecture, battery size, and environmental impact is strongly dependent on battery technology
- Even the technologies deemed as “good” indicative guides only act as good indicators when applied to specific vehicle applications and duty cycles. Very few technologies can be viewed as “blanket” indicative measures regardless of vehicle implementation

7 technologies have been identified as potential indicative guides for CO_2 benefit due to limited fields of application and narrow benefit ranges

- From the technologies reviewed, those identified as potential indicators for CO_2 reduction and which are not significantly affected by the above are:
  - ***Aerodynamic trailers – 10% potential CO_2 reduction***
    - For heavy duty long haul applications, if no change to existing tractor unit
  - ***Electric Vehicle Bodies – 10% - 20% potential CO_2 reduction (depending on body type)***
    - Applies to a limited portion of the market
  - ***Air compressor – 1.5% potential CO_2 reduction***
    - For HD applications
  - ***Mechanical Turbocompound – 3 – 5% potential CO_2 reduction***
    - For HD applications
  - ***Electric Vehicles – 100% potential tailpipe CO_2 reduction***
    - Zero tailpipe CO_2
  - ***CNG – 10% - 15% potential CO_2 reduction***
    - If dedicated CNG engine
  - ***Fuel Cell – 100% potential tailpipe CO_2 reduction***
    - Zero tailpipe CO_2
- For the above listed technologies, either the technology is limited to a certain application, so CO_2 benefit range is limited or it is constant across different duty cycles and vehicle applications or tailpipe CO_2 is zero
- The remaining technologies are affected too much by the type of vehicle application, duty cycle and other external factors to be used as an indicative guide

Specify a low carbon truck - which technologies to trial?

- Any trial must be scientifically controlled, properly designed and statistically significant
- Ricardo suggests a modular trialling structure which is scalable and could allow different technology combinations to be evaluated:
  - ***Aerodynamic trial (trailer)***
    - Evaluate a fully integrated off the shelf aerodynamic trailer (e.g. Don-Bur Teardrop) against a standard trailer adding progressively a range of aerodynamic aids (e.g. fairings, diffusers, spray flaps, boat-tail plates)
  - ***Rolling resistance trial (trailer and tractor)***
    - Low rolling resistance tyres (long term durability and lifetime economic cost), vs. SWT, with/without automated tyre pressure monitoring
    - Could include this with the aero trial
  - ***Driver behaviour trial (tractor)***
    - Predictive cruise control
  - ***Engine trial (tractor)***
    - EGR vs. SCR at E4/E5 – is there an inherent advantage in one technology pathway?
    - Mechanical vs. electrical turbocompounding
    - Progressive addition of low CO_2 engine accessories to a baseline engine (e.g. variable water pump, low oil viscosity, variable air compressor, air hybrid, variable power steering pump, variable fan)
  - ***Niche vehicles trial (trailer and tractor where applicable)***
    - Electric bodies e.g. for normally hydraulic refuse truck
    - Alternative reefer systems
  - ***Electric vehicle trial***
    - Back to back long term evaluation of electric vs ICE delivery van (e.g. Smiths Newton vs Transit), examining long term performance, range limitations, maintenance burden, full life costs, emissions, noise

To successfully trial technologies collaboration of partners is required to achieve meaningful results

- Trialling this wide range of technologies is not going to be cheap, and so the collaboration of a partner or ideally a consortium would be required
- The partners would ideally include fleet operators since have a large incentive to reduce fuel costs and are likely to be able to tolerate/manage any potential disruption caused by the fleet trial. They are also more likely to run a consistent set of routes which will make evaluation more rigorous. It is envisaged that the selection of fleet partners could be done on a competitive bidding basis
- However use of a single fleet will generally restrict the trial to a fixed commodity being transported (e.g. groceries by a supermarket, bulk parcels by a logistics firm, aggregates by a bulk materials haulier) and this may limit the widespread validity of the results
- Other partner organisations could include providers of vehicle technology but the neutrality of the trial must be maintained
- Base lining and trialling should be carried out over a long period to eliminate seasonal variation in fuel consumption
- To minimise intrusion onto the large number of fleet vehicles, it is anticipated that sufficient information on instantaneous fuel flow will be available from the existing vehicle trip computer/tachograph. If this is not sufficient either data loggers, which intercept engine ECU fuelling commands, or an on-engine flow meter could be installed. In every case these instantaneous measurements would be supplemented by accurate brim-to-brim refuelling volumes. Fuel consumption can readily be converted to CO_2 figures.
- Modifications to the vehicles as type approved may require the co-operation and approval of VOSA or other appropriate regulatory bodies
- Biofuels have not been included in the trial. Their primary CO_2 reduction contribution is in the way they are produced not in the way they are burned. Principal risks associated with biofuel operation are associated with engine durability and it is not recommended that DfT involve themselves in this area which is already investigated by engine manufacturers

Contents

- Abbreviations and Acronyms
- **Terminology**
- Introduction
- Technology Identification
- Feasibility Analysis
- Technology Summary
- **Conclusions and Further Work**

From a review of low carbon technologies for HGVs, the most promising for CO_2 reduction have been identified along with market entry timeframe

- Aerodynamic trailers, electric bodies & vehicle platooning offer the most promising CO_2 reduction potential for vehicle technologies
  - Near term vehicle technologies are electric bodies and aerodynamic trailers, with vehicle platooning a long term technology with commercial challenges to overcome
- Powertrain technologies electric vehicles, fuel cells and full hybrids offer greatest tailpipe CO_2 reduction but not without limitations
  - Near term powertrain technologies include alternative powertrains of electric vehicle and full hybrids with medium term technologies being fuel cells, fuel cell APUs and stop/start hybrid systems
- Fuel technologies with greatest lifecycle CO_2 benefit are biogas, biofuels and hydrogen, however tailpipe reductions are lower
  - First generation biofuels and biogas offer the greatest CO_2 benefit in the near term for fuel technologies however availability will be limited
  - Medium term technologies include BTL, HVO, Hydrogen and CNG of which CNG offers the lowest CO_2 reduction
- 7 of the technologies reviewed have been identified as potential indicators for CO_2 benefit due to their limited fields of application and narrow benefit ranges associated with it, and include:
  - Aerodynamic trailers – for heavy duty long haul applications, if no change to existing tractor unit
  - Electric Vehicle Bodies – applies to a set portion of the market
  - Air compressor – for HD applications
  - Mechanical Turbocompound – for HD applications
  - Electric Vehicles – zero tailpipe CO_2
  - CNG – if dedicated CNG engine
  - Fuel Cell – zero tailpipe CO_2

There are a number of areas where this review could be expanded into further work and details are given

- **Full lifecycle analysis of different low carbon technologies**
  - A more in-depth lifecycle analysis could be conducted for one or more technologies to get a much better understanding of the impact of the technology at every point in its life and to ensure that low carbon technologies have lower lifecycle CO_2 emissions than technologies they are replacing
- **Expansion of the technologies reviewed**
  - Expand the number of technologies reviewed to include those that were not possible in the given time frame
  - Technologies that may be included in this are:
    - Electric cooling fans
    - Electric Air conditioning
    - Fuel injection systems - reduce power consumption
    - Servo steering pumps
    - Shock absorbers to recover energy
    - Fly-wheel technology as energy storage system
- **Scenario modelling of the effect of the most promising low carbon technologies on the CO_2 emissions of the vehicle fleet**
  - Detailed scenario modelling of the uptake of the most promising low carbon technologies on the vehicle fleet
  - Requires analysis/audit of the existing fleet and a timeframe over which the introduction of technologies would be adopted. This should include tachograph or other analysis of real fleet operating behaviour
- **Fleet trialling of some of the more promising technologies to better understand their real world benefit and limitations**
  - Technologies which would benefit from fleet trials may include low rolling resistance tyres, full hybrid systems and electrification of vehicle bodies