RICARDO

"Support for Updating the RAINS Model Concerning Road Transport" Final Report

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Glossary of Abbreviations

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Abbreviation	Explanation
4-way Catalyst	Catalyst for NOx, HC, CO and Particulates
CGI	Direct Gasoline Injection (Mercedes trade mark)
CR	Common Rail fuel injection system
DI	Direct Injection
DPF	Diesel Particulate Filter
DOC	Diesel Oxidation Catalyst
ECU	Electronic (engine) Control Unit
EGR	Exhaust Gas Recirculation (NOx or FE improvement)
EUI	Electronic Unit Injector
EUP	Electronic Unit Pump
FE	Fuel Economy
FIE	Fuel Injection Equipment
GDI	Gasoline Direct Injection
GVW	Gross Vehicle Weight (mass when loaded)
HCCI	Homogenous Charge Compression Ignition
HDT	Heavy Duty Truck (12000kgs and above)
IDI	Indirect Injection
ISG	Integrated Starter Generator
LDT	Light Duty Truck (up to 3500kgs GVW)

Abbreviation	Explanation
LNT	Lean NOx Trap (traps NOx for later conversion)
MDT	Medium Duty Truck (3500kgs to 12000kgs GVW)
MPI	Multi-Point Injection
MPFI	Multi-Point Fuel Injection (same as MPI)
MPV	Multi-Person Vehicle (people carrier, usually 7 seater)
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer (car maker)
Oxy Catalyst	Oxidation Catalyst (treats HC and NOx)
Pmax	Maximum cylinder pressure
SCR	Selective Catalytic Reduction (needs Urea)
SIDI	Spark Ignited Direct Injection (Same as GDI)
Stoich	Stoichiometric mixture (Chemically balanced)
SUV	Sport Utility Vehicle (e.g. Landrover Freelander)
VCO	Valve Closing Orifice
VGT	Variable Geometry Turbocharger
VNT	Variable Nozzle Turbocharger (same as VGT)
VVA	Variable Valve Actuation
VVT	Variable Valve Timing

Contents

Introduction

- Study completed in response to contract 03-1
- Main aim to provide CITEPA with information pertaining to the cost and benefit of emissions equipment across all cars and trucks for input to the RAINS model
  - Matrix of required information provided as part of Ricardo proposal
- Study completed using various sources
  - Paper study (SAE, Ricardo library, databases, etc)
  - Past and current test experience
  - Customer sources (confidential base data)
  - Expert opinion
- Source data analysed to produce information for the Matrix

Contents

Approach

- Split the total European fleet into categories in line with exhaust emissions legislation
  - Gasoline car
    - Engine sizes 1200cc to 2000cc excluding “performance” vehicles (e.g. GTI’s)
  - Gasoline Light Duty Truck (LDT)
    - Up to 3500kg Gross Vehicle Weight
  - Diesel car
    - Engine sizes 1500cc to 2000cc
  - Diesel LDT
    - Up to 3500kg Gross Vehicle Weight (GVW)
  - Diesel medium duty truck
    - 3500kg to 12,000kg GVW
  - Diesel heavy duty truck
    - 12,000kg GVW and above

Approach

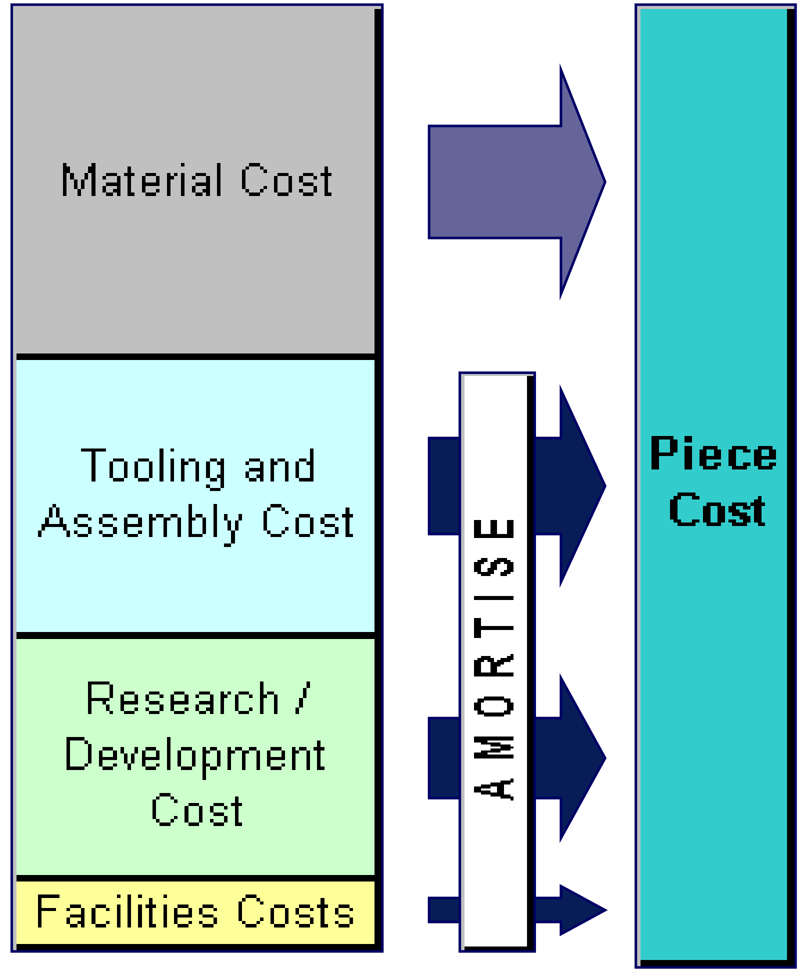
- Determine mainstream technologies for each category and level of European emissions legislation
  - Understand the effect of these technologies from a quantitative and theoretical perspective
- Determine secondary technologies and future expectations
- Perform searches to determine
  - Cost to manufacture and maintain
  - Regulated emissions and fuel economy
  - Unregulated emissions
- Determine proportions within the fleet using each technology
- Amortise manufacturing and maintenance costs across the fleet for each sector to produce an on-cost per vehicle

Approach

- Cost to manufacture includes
  - Cost information from several OEM sources
  - Tooling costs from Ricardo experts and OEM sources
  - Additional test equipment information from Ricardo experience
  - Development and calibration-costs from Ricardo experience
  - Tooling and piece costs vary significantly for many reasons. Engineering judgement used to produce a reasonable figure.
  - Costs amortised for production volumes over 100,000 units per year
    - Manufacturing level at which tooling costs can reasonably be absorbed
  - Costs vary significantly from first introduction through to when a technology is established. The established cost has been used in all cases.

Approach

- Costs to supply a new technology come from four main areas which are amortised to give the "piece cost"
  - Materials (plastics, metals, fasteners, gaskets, electronic circuit boards, etc) Note: Source data already per vehicle basis
  - Tooling (cost to build the material forming and assembly lines) – Amortised
  - Development cost (increasingly significant) – Amortised
  - New facilities required by the OEM to support a new technology – Amortised

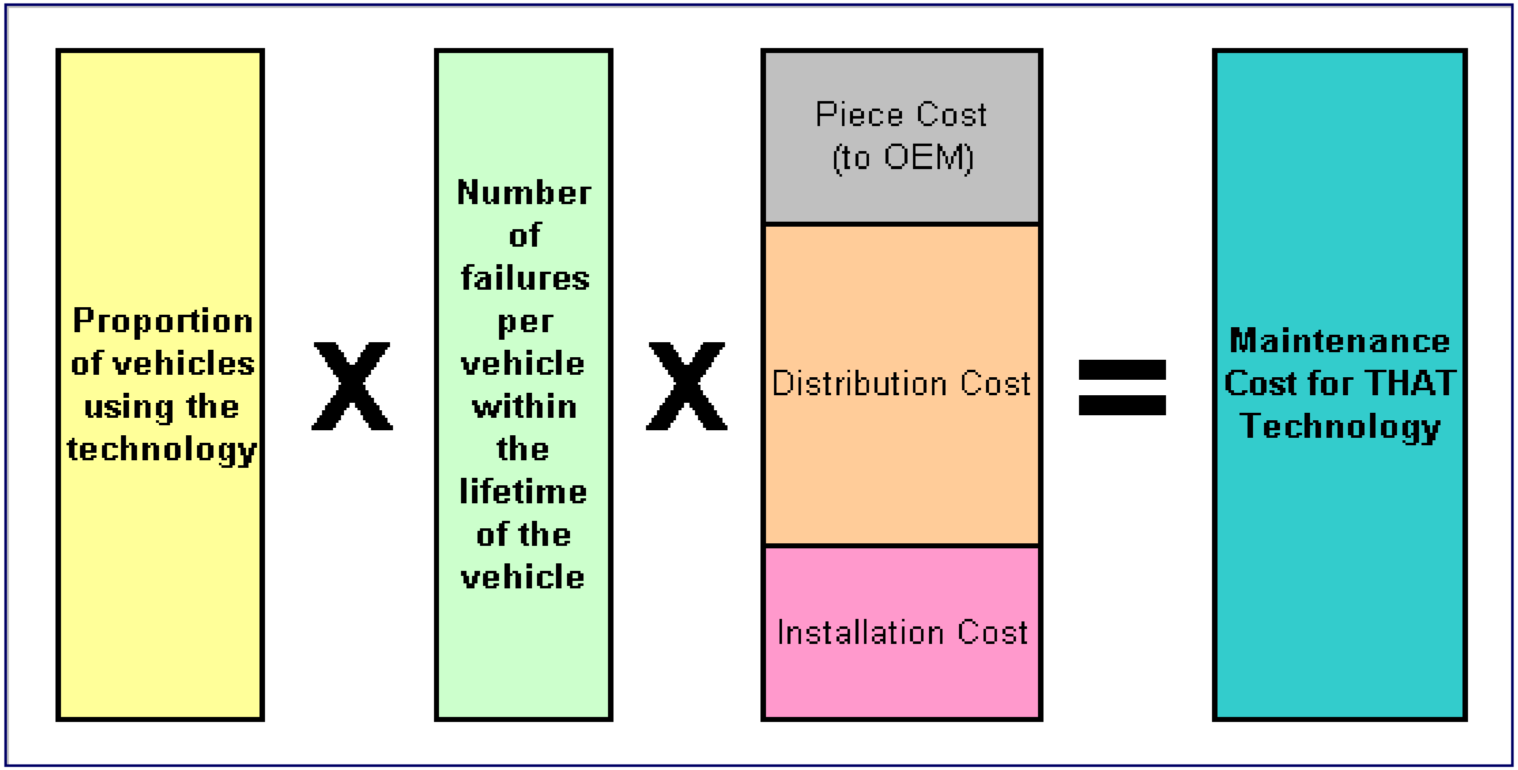


Approach

- Maintenance Cost
  - Warranty costs are a closely guarded secret
  - Estimation made based on reliability seen during development
  - Cost to customer estimated at 5 x cost to OEM (includes supply, delivery and fitting).
  - Taxation not included
  - Costs **do not include routine servicing** unless specifically related to emissions equipment
    - Difficult to account for increased reliability
    - Variation in inspection quality among EU countries
    - Variation in inspection and labour costs among EU countries
  - Assumed that part only replaced if
    - Failure results in illumination of the OBD warning light, or
    - Vehicle fails inspection, or
    - Notable impact on vehicle performance (poor idle, low performance, noise, etc.)

Approach

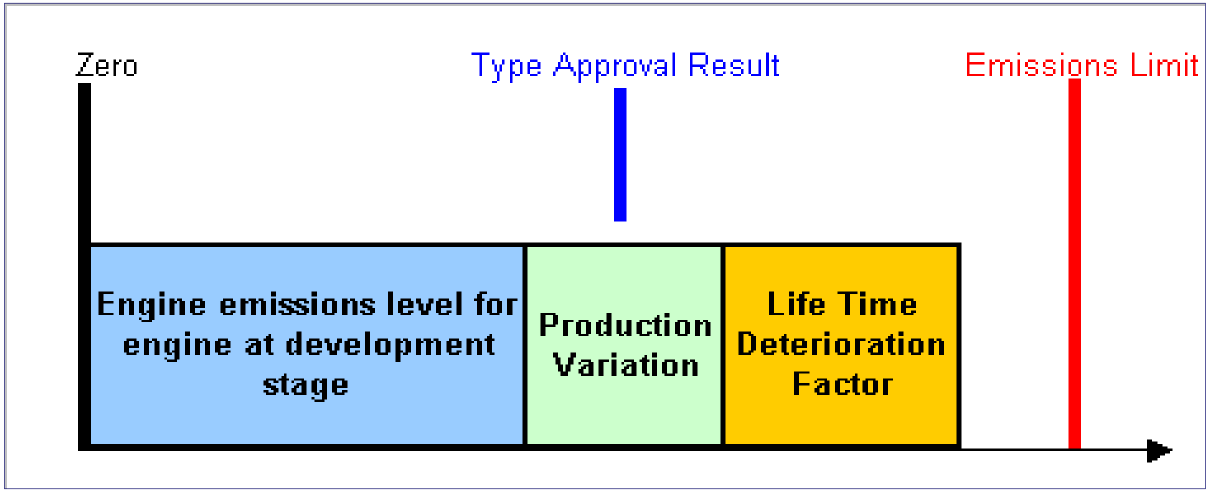
- Maintenance Costs: Determined by considering each technology in turn



- Then sum for all technologies to give a maintenance cost for the “average” vehicle

Approach

- Exhaust emissions (main information sources):
  - Published data from **British Vehicle Certification Authority** (VCA) and **German Federal Transport Authority** (KBA) - certification tests results on new vehicles
    - Only data from European Urban drive cycle has been used (ignoring Extra-urban cycle data which became necessary at Euro 1) as previous data did not exist. Change in standards at Euro 3 taking into account first 40 second warm up period are deemed to have negligible impact upon fuel consumption when compared with other factors
  - Internal test data
  - Expert engineering judgement



Note: Certified emissions levels are based upon maintaining a margin of safety beyond an engineering margin for production variation and another for deterioration of emissions equipment during the life of the vehicle. Emissions data quoted is for nearly new vehicles

Approach

- Shed (evaporative) emissions have not been included in this study
  - **Lack of available data** detailing evaporative emissions before legislation came in
  - **Difficult to assess exact impact of evaporative emissions** compared to drive cycle emissions as it is difficult to assess how much time an average vehicle spends at rest
  - **Evaporative emissions legislation** significantly reduces evaporative HC emissions (current limit is 2gram / 48hour test)
  - **Costs of evaporative emissions equipment, calibration and software, etc**, have been taken into account
- Evaporative emissions are only a consideration for gasoline powered vehicles

Contents

Technology Selections

- The following were identified for each category
  - Types of vehicle
  - Technology within them
  - Understanding of how any new technology works along with current challenges to meet future emissions legislation
- Experience used to understand how these technologies have changed
  - "Unabated" baseline = typical 1990 (pre-emissions legislation)
- Research data and theory to determine how these changes effect fuel economy and emissions
  - Data does not always produce expected results
  - Effected by factors such as increased vehicle mass due to increasing size, equipment and crashworthiness

Gasoline Powered Cars and LDT's

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- Car and LDT engines use similar technology with cars leading the way
- Circa 1990 most cars still using carburettors
  - Unleaded fuel being promoted by Governments
  - Use of catalytic converters by top-end manufacturers, e.g. Audi
- Development has been mostly in terms of catalyst loading and location
- Other technologies such as roller cam followers and variable valve timing have helped reduce fuel consumption
- Growth area is now gasoline direct injection and lean operation, requiring Lean NOx Trap (LNT)

Gasoline Technology Roadmap

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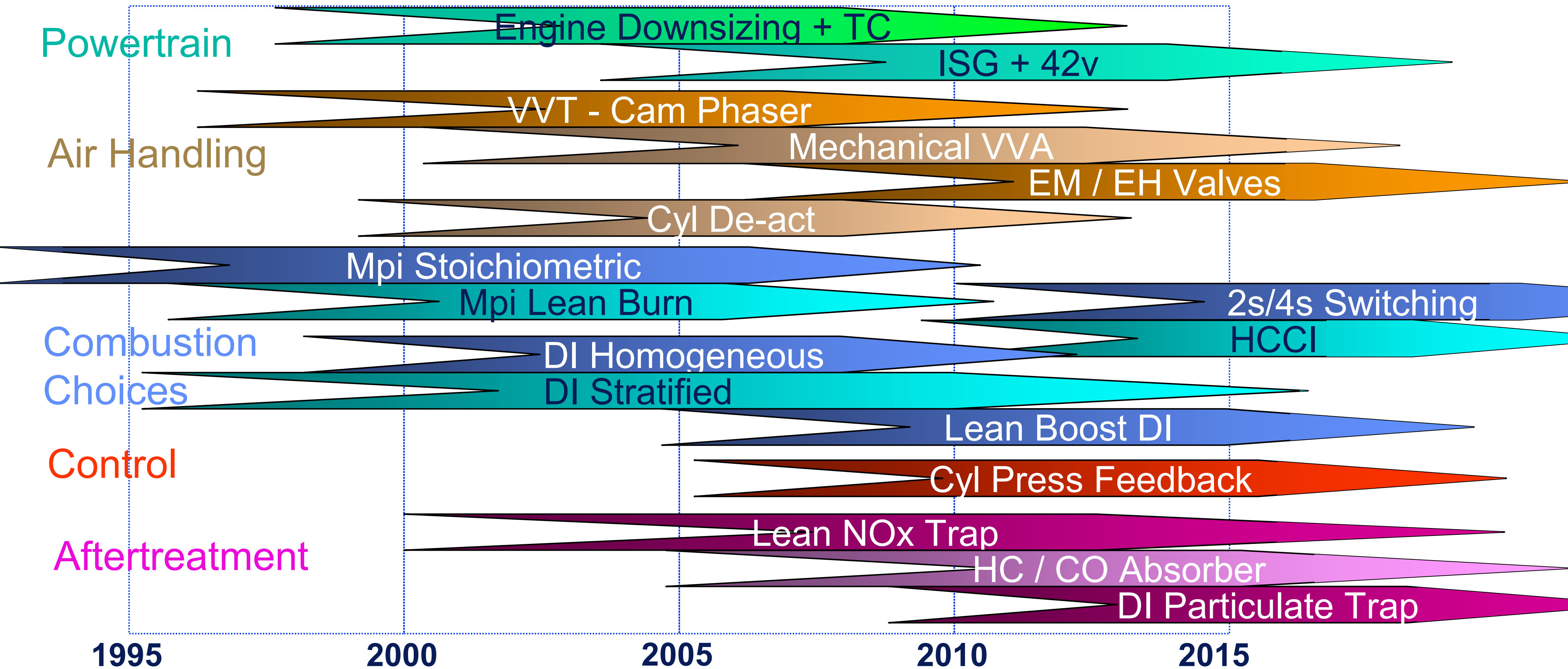
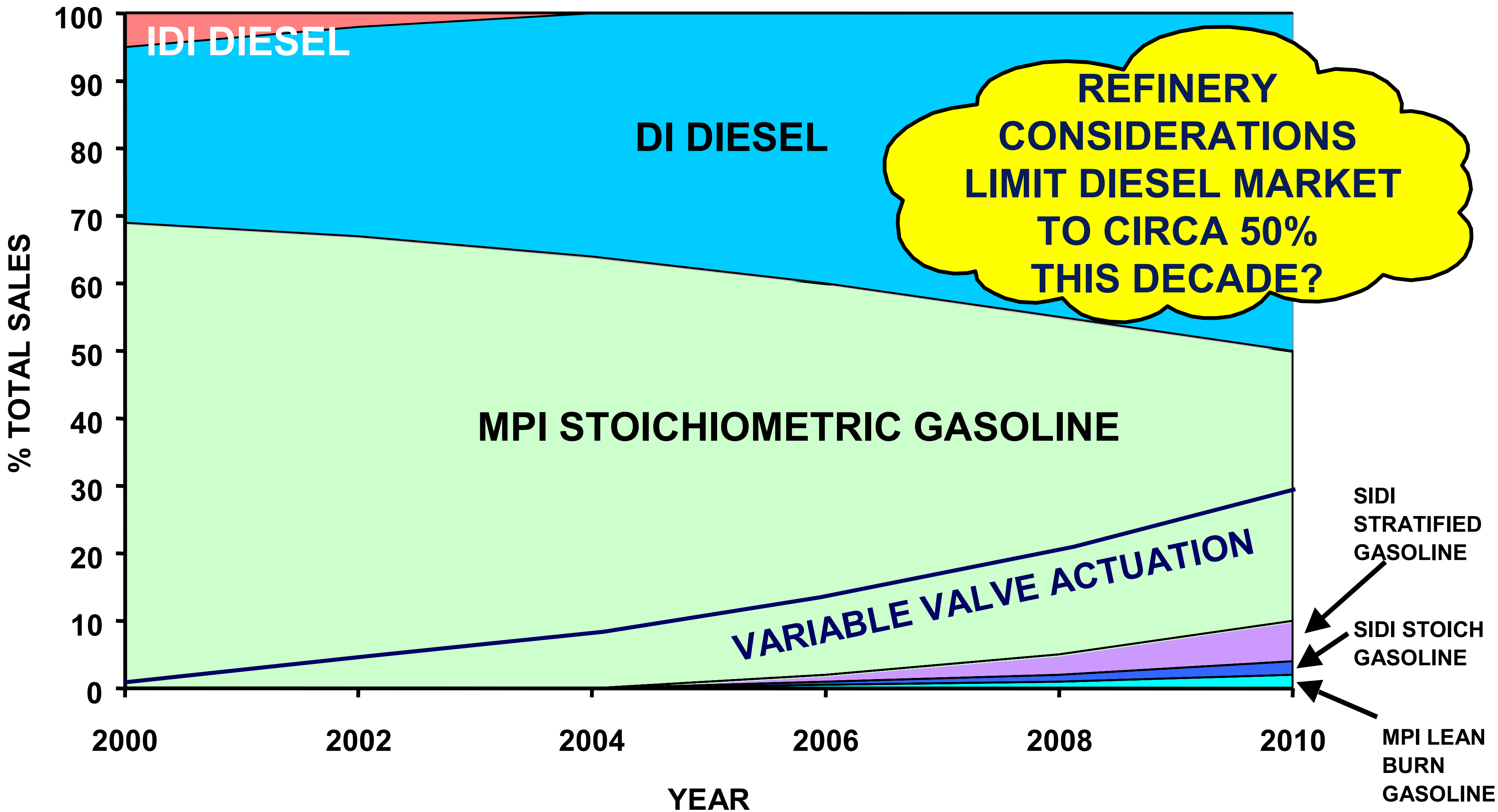
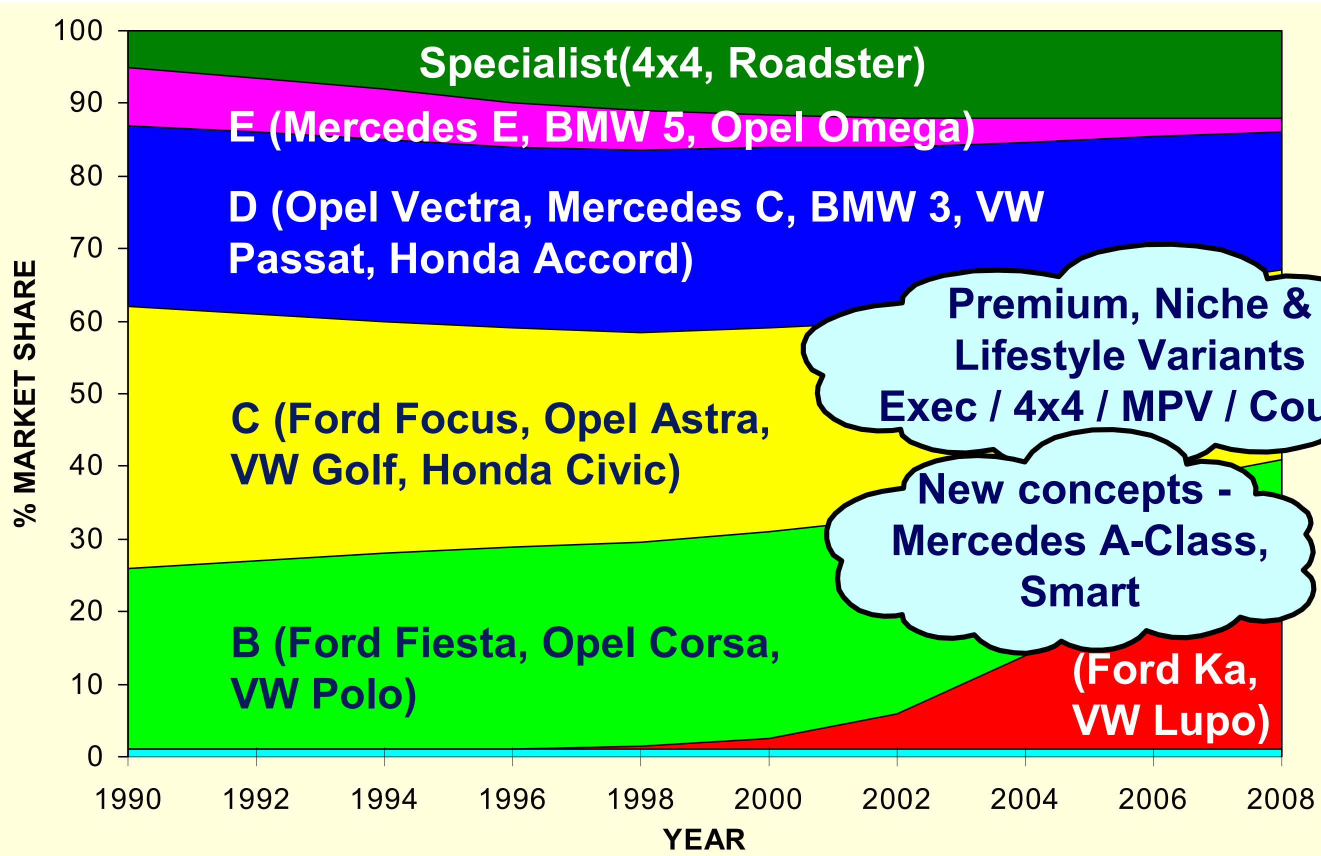
- **Will respond to CO_2 pressures even in strongly Dieselised markets**
- **Critical technologies:** Next steps beyond VVA vs DI vs Downsize, Cost down especially in lower segments, premium / sports products without CO_2 embarrassment



European Passenger Car Technology Mix



European Passenger Car Market Share By Vehicle Segment



- **Sub-B growth strong but limited**
  - Limited ability to carry family / lifestyle equipment
- **Migration from larger vehicles to C & D class**
  - But to premium brands within those classes
- **Executive, SUV & MPV based on C & D-class platforms**

Expected Technology Penetration: Gasoline Car

Euro Emissions Standard	0	1	2	3	4	5	6
Year of Introduction:	**< 1992 (1990)**	**1992**	**1996**	**2000**	**2005**	**2010**	**2015**
Emissions Technology Requirement (Majority of Vehicles)	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
On Board Diagnostics							
OBD Equipped	0	0	1	99	100	100	100
FUEL INJECTION EQUIPMENT							
Carburettor	60	2	0	0	0	0	0
Single Point fuel injection	10	43	15	12	10	5	0
Multi point fuel injection	30	55	84	87	85	80	70
Gasoline direct injection	0	0	0	1	5	15	30
IGNITION SYSTEMS							
Distributor	65	5	0	0	0	0	0
Electronic Ignition	35	85	30	10	2	0	0
Distributorless electronic ignition	0	10	70	90	98	100	100
NOx REDUCTION STRATEGY							
Exhaust Gas Recirculation	0	0	20	85	55	25	5
Variable cam/valve timing	0	0	0	1	45	75	95

Expected Technology Penetration: Gasoline Car

Euro Emissions Standard	0	1	2	3	4	5	6
Year of Introduction:	**< 1992 (1990)**	**1992**	**1996**	**2000**	**2005**	**2010**	**2015**
Emissions Technology Requirement (Alternative)				Direct Injection / Lean Nox trap / wide range lambda / evaporative emissions system as above		Revised injectors / combustion system improvements / higher injection pressure / variable cam phasing	Mild or Parallel hybrid
AFTERTREATMENT							
Three way underfloor catalyst	15	100	100	90	25	15	10
Three way close coupled catalyst	0	0	0	10	75	85	90
Starter / Light off catalyst	0	0	0	20	25	15	10
Lambda sensor	15	99	0	0	0	0	0
Heated lambda sensor	0	0	100	90	70	25	0
Wide range lambda sensor	0	0	0	10	30	75	100
Post Catalyst O2 sensor	0	0	20	100	100	100	100
Secondary Air Injection	0	1	2	2	2	2	3
Closed loop secondary air injection	0	0	0	0	2	2	5
Lean-Nox trap	0	0	0	1	5	15	30
Thin walled exhaust manifold	0	1	1	1	1	1	1
Evaporative emissions equipment (purge valve, canister, etc)	0	100	100	100	100	100	100
ALTERNATIVE TECHNOLOGY							
Auto engine off at idle	1	0	0	0	0	5	25
Mild or parallel hybrid	0	0	0	0	0	2	15
Boosted Direct Injection	0	0	0	0	0	1	5
HCCI	0	0	0	0	0	0	1
Variable compression ratio	0	0	0	0	0	0	1
REVISIONS							
Improved combustion chamber design	100	100	100	100	100	100	100
Electronic Control System	15	99	100	100	100	100	100
Improved calibration and control	100	100	100	100	100	100	100

Evaporative emissions: Market penetration and cost

- Requirement for evaporative emissions control has existed since Euro 1.
- Requirements tightened over Euro 1 and Euro 2 and so cost of additional equipment increased significantly from first introduction.
- Estimated cost to the manufacturer of evaporative emissions equipment in the year 2000 was €40 to €50. However this is highly dependant on the manufacturer, the design of the system, and the volumes being produced.

Expected Technology Penetration: Gasoline LDT

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Euro Emissions Standard	0	1	2	3	4	5	6
Year of Introduction:	< 1992 (1990)	1992	1996	2000	2005	2010	2015
Emissions Technology Requirement (Majority of Vehicles)	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
On Board Diagnostics							
OBD Equipped	0	0	1	99	100	100	100
FUEL INJECTION EQUIPMENT							
Carburettor	80	1	0	0	0	0	0
Single Point fuel injection	15	29	20	15	5	2	0
Multi point fuel injection	5	70	80	85	94	96	95
Gasoline direct injection	0	0	0	0	1	2	5
IGNITION SYSTEMS							
Distributor	65	5	0	0	0	0	0
Electronic Ignition	35	85	45	15	2	0	0
Distributorless electronic ignition	0	10	55	85	98	100	100
NOx REDUCTION STRATEGY							
Exhaust Gas Recirculation	0	0	20	85	55	25	5
Variable cam/valve timing	0	0	0	1	25	60	95

Expected Technology Penetration: Gasoline LDT

Euro Emissions Standard	0	1	2	3	4	5	6
Year of Introduction:	< 1992 (1990)	1992	1996	2000	2005	2010	2015
Emissions Technology Requirement (Majority of Vehicles)	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
AFTERTREATMENT							
Three way underfloor catalyst	15	100	100	90	25	15	10
Three way close coupled catalyst	0	0	0	10	75	85	90
Starter / Light off catalyst	0	0	0	20	25	15	10
Lambda sensor	15	99	0	0	0	0	0
Heated lambda sensor	0	0	100	90	70	25	0
Wide range lambda sensor	0	0	0	10	30	75	100
Post Catalyst O2 sensor	0	0	20	100	100	100	100
Secondary Air Injection	0	0	0	0	0	1	2
Closed loop secondary air injection	0	0	0	0	2	2	5
Lean-Nox trap	0	0	0	0	1	2	4
Thin walled exhaust manifold	0	1	1	1	1	1	1
Evaporative emissions equipment (purge valve, canister, etc)	0	100	100	100	100	100	100
ALTERNATIVE TECHNOLOGY							
Auto engine off at idle	0	0	0	0	0	5	15
Mild or parallel hybrid	0	0	0	0	0	0	3
Boosted Direct Injection	0	0	0	0	0	0	1
HCCI	0	0	0	0	0	0	0
Variable compression ratio	0	0	0	0	0	0	0
REVISIONS							
Improved combustion chamber design	100	100	100	100	100	100	100
Electronic Control System	15	99	100	100	100	100	100
Improved calibration and control	100	100	100	100	100	100	100

Diesel Powered Cars

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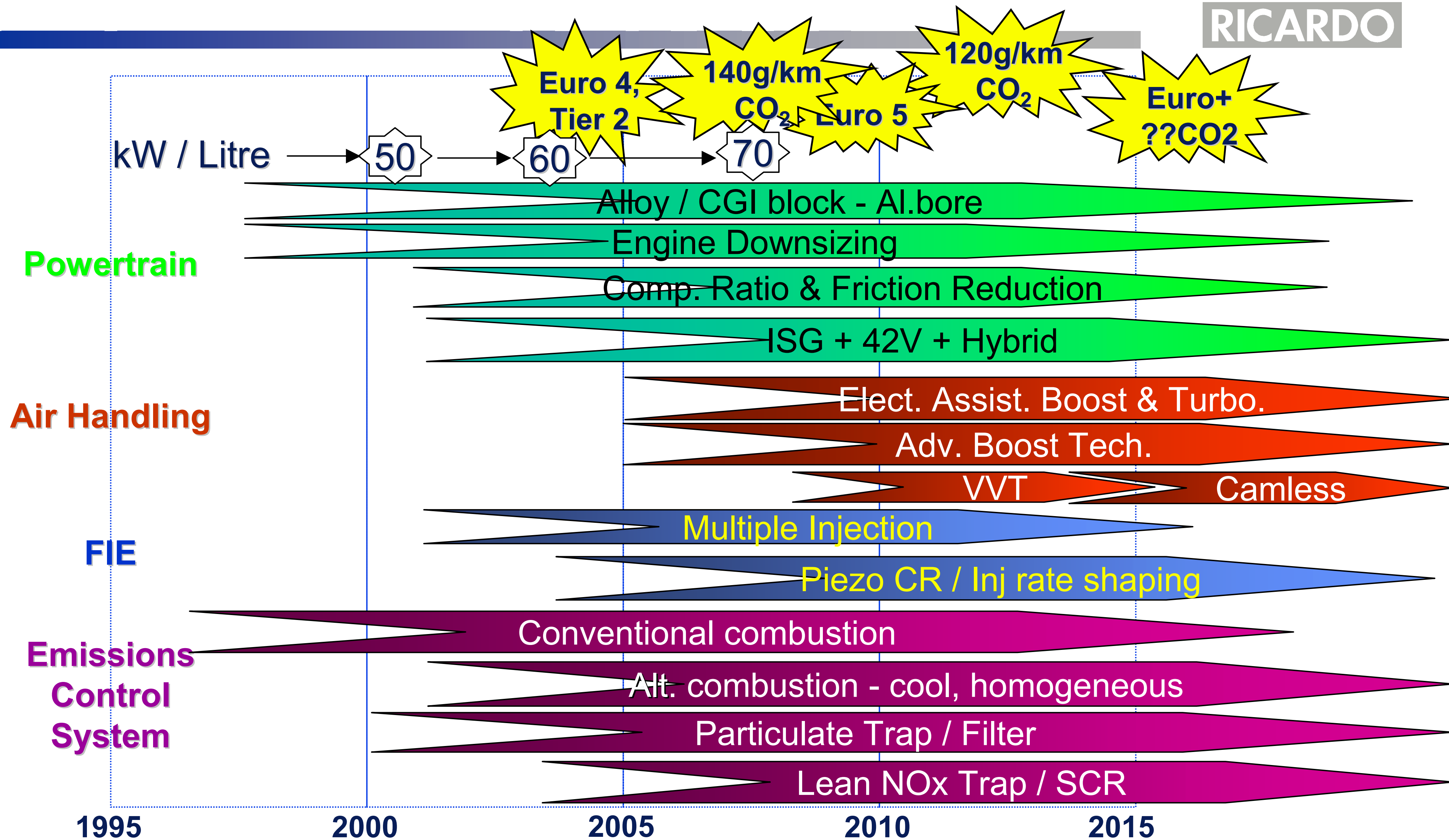
- Diesel cars in 1990 tended to be mechanical “intermediate pressure pump” fuelled indirect injection (IDI)
- Most were normally aspirated
- Turbochargers were introduced to improve performance
- Direct Injection (DI) move to improve fuel economy and emissions
- Electronics introduced to enable better control - timing and fuel pressure, improve power and reduce noise
- To date, after-treatment limited to oxidation catalysts where necessary
- Lean NOx Trap (LNT) technology is being developed for diesel use

Technical Strategy - Euro 5 (0.08g/km NOx)

DIESEL	Engine	FIE	Aftertreatment
B SEGMENT **1140kg**	1.1 to 1.4 litre DI TC & VNT I4 cylinder 4v Fe or Al block & bore	Piezo Common rail 1600 bar Multiple injection	Oxidation cat. DPF
C SEGMENT **1360kg**	1.2 to 1.8 litre DI VNT I4 Fe / Al block & bore 4v v-swirl Hi -Boost systems	Piezo Common rail 1600 - 1800 bar Multiple injection	Oxidation cat. DPF
C/D SEGMENT **1590kg+**	1.5-2.5 litre DI TCA-VNT 4v v-swirl CGI / Fe / Al block & bore Hi -Boost systems	Piezo Common rail 1800-2000 bar Multiple injection	Oxidation cat. DPF LNT?
D/E SEGMENT **SUV** **1710kg+**	2.0-5.0 litre DI TCA-VNT I4, I5 V6 and V8 4v v-swirl CGI / Al block & bore Hi -Boost systems	Piezo Common rail 1800-2000 bar Multiple injection	Oxidation cat. DPF LNT

Diesel Technology Roadmap



Emissions Roadmap

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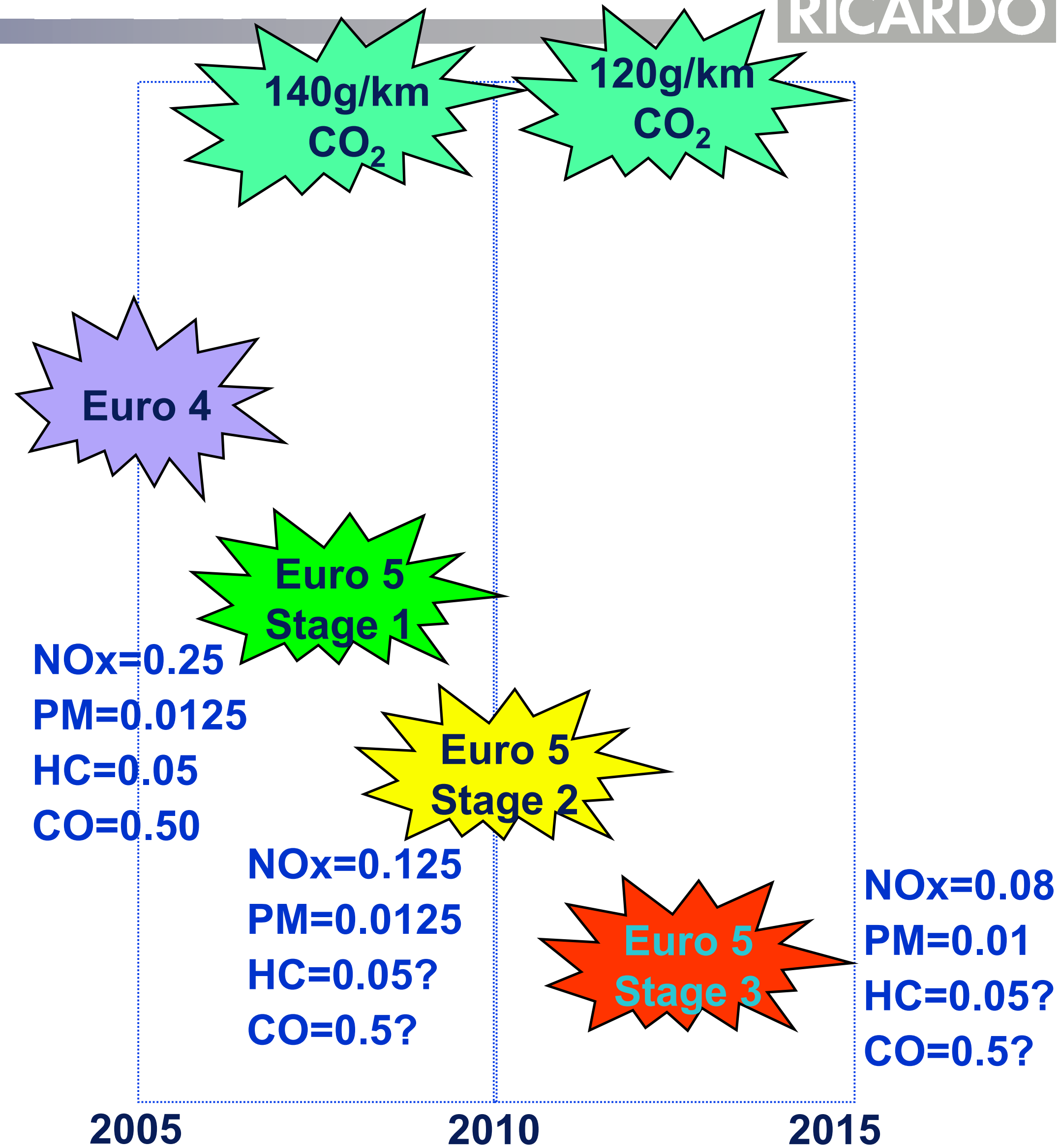
Emissions for 2010+

- CO2 ACEA targets fixed
- Euro 5 legislation NOT fixed
  - Staged introduction?
  - Emission levels?
  - Methodologies?
    - PM measurement
    - PM & NOx trap homologation
- Harmonisation with gasoline
  - Gas. Euro 4 NOx
  - Gas. Euro 5 HC CO = 50% gas. Euro 4 = Euro 4 diesel
    - why go lower?
  - Worse case gas. Euro 5 NOx=0.04



Expected Technology Penetration: Diesel Car & LDT

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Euro Emissions Standard	0 (ECE R15/04)	1	2	3	4	5 (draft)
Year of Introduction:	< 1992	1992	1996	2000	2005	2010
Emissions Technology Requirement (Majority of Vehicles) - Incremental	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Mechanical / part-electrical fuel-control / IDI combustion system / Low pressure injectors / EGR system with electric control	Electric fuel timing/metering / cooled EGR circuit / Turbocharged	DI combustion system (HP injectors) / turbocharged, intercooled, Diesel oxidation catalyst	4V cylinder head design	2nd generation common rail or unit injectors, variable nozzle turbocharger, (catalysed) Diesel particulate filter, modulated EGR and/or Lean NOx trap
FUEL INJECTION EQUIPMENT						
indirect mechanical injection (rotary pump)	93	85	28	0	0	0
mechanical direct injection (rotary pump)	7	0	0	0	0	0
electric indirect injection (rotary pump)	0	0	43	29	1	0
electric direct injection (rotary pump)	0	15	28	38	6	0
electric direct injection (rotary pump - gen	0	0	1	4	1	0
electronic unit injectors (gen 1)	0	0	0	4	0	0
electronic unit injectors (gen 2)	0	0	0	0	20	13
common rail (gen 1 - 1300 bar)	0	0	0	25	6	0
common rail (gen 2 - 1600 bar)	0	0	0	0	51	21
common rail (gen 3 - 1800/2000 bar / piezo-electric activation)	0	0	0	0	15	66
CONTROL SYSTEM						
ECU and WIRING	0	100	100	100	100	100

Expected Technology Penetration: Diesel Car & LDT

Euro Emissions Standard	**0** (ECE R15/04)	**1**	**2**	**3**	**4**	**5 (draft)**
Year of Introduction:	**< 1992**	**1992**	**1996**	**2000**	**2005**	**2010**
Emissions Technology Requirement (Majority of Vehicles) - Incremental	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Mechanical / part-electrical fuel-control / IDI combustion system / Low pressure injectors / EGR system with electric control	Electric fuel timing/metering / cooled EGR circuit / Turbocharged	DI combustion system (HP injectors) / turbocharged, intercooled, Diesel oxidation catalyst	4V cylinder head design	2nd generation common rail or unit injectors, variable nozzle turbocharger, (catalysed) Diesel particulate filter, modulated EGR and/or Lean NOx trap
AIR MANAGEMENT						
naturally aspirated	79	66	44	15	7	0
wastegated turbocharger	21	34	49	71	44	29
intercooler	9	17	38	52	71	89
variable nozzle turbo	0	0	7	14	49	69
two-stage turbocharging	0	0	0	0	0	2
intercooler by-pass (for start-up)	0	0	0	0	1	15
4V per cylinder	0	3	5	28	73	92
inlet port deactivation (variable swirl)	0	0	2	4	16	46
NOx REDUCTION						
EGR circuit	0	85	100	100	100	100
EGR cooler	0	15	56	78	92	98
modulated EGR cooling	0	0	0	0	5	27
AFTER TREATMENT						
Diesel oxidation catalyst	0	0	10	100	100	100
2nd Diesel oxidation catalyst	0	0	0	5	10	15
Diesel particulate filter	0	0	0	1	9	31
Catalysed Diesel particulate filter	0	0	0	0	8	69
Lean NOx trap	0	0	0	0	1	25
Selective Catalytic Reduction (Urea required)	0	0	0	0	0	5

Diesel Powered LDT’s

- By 1990 many larger engines were already DI, but most were still normally aspirated
- LDT 1, 2 & 3 use car technology
- Similar technology path to cars, with fuel consumption primary development attribute
- End result the same, engines now tend to be electronic control direct injection. Most turbocharged, many aftercooled. Widespread use of cooled EGR.
- Oxidation catalysts common for Euro3
- Diesel Particulate Filters (DPFs) introduced for some Euro 4 vehicles, mandatory for Euro 5
- Technologies similar to passenger car






Medium Duty Truck Engines

- Direct injection adopted for rating and fuel economy before introduction of Euro emissions legislation
- Engines became turbocharged, and/or turbocharged with aftercooling to meet Euro 2 emissions legislation
- Significant developments include
  - 2 valve to 3 or 4 valves per cylinder
  - Injectors moved to centre of combustion chamber
  - Increased injection pressures and improved injection control
  - Nozzle technology
  - Expect to see further development of these, along with increased use of EGR and introduction of after-treatment technologies in the future

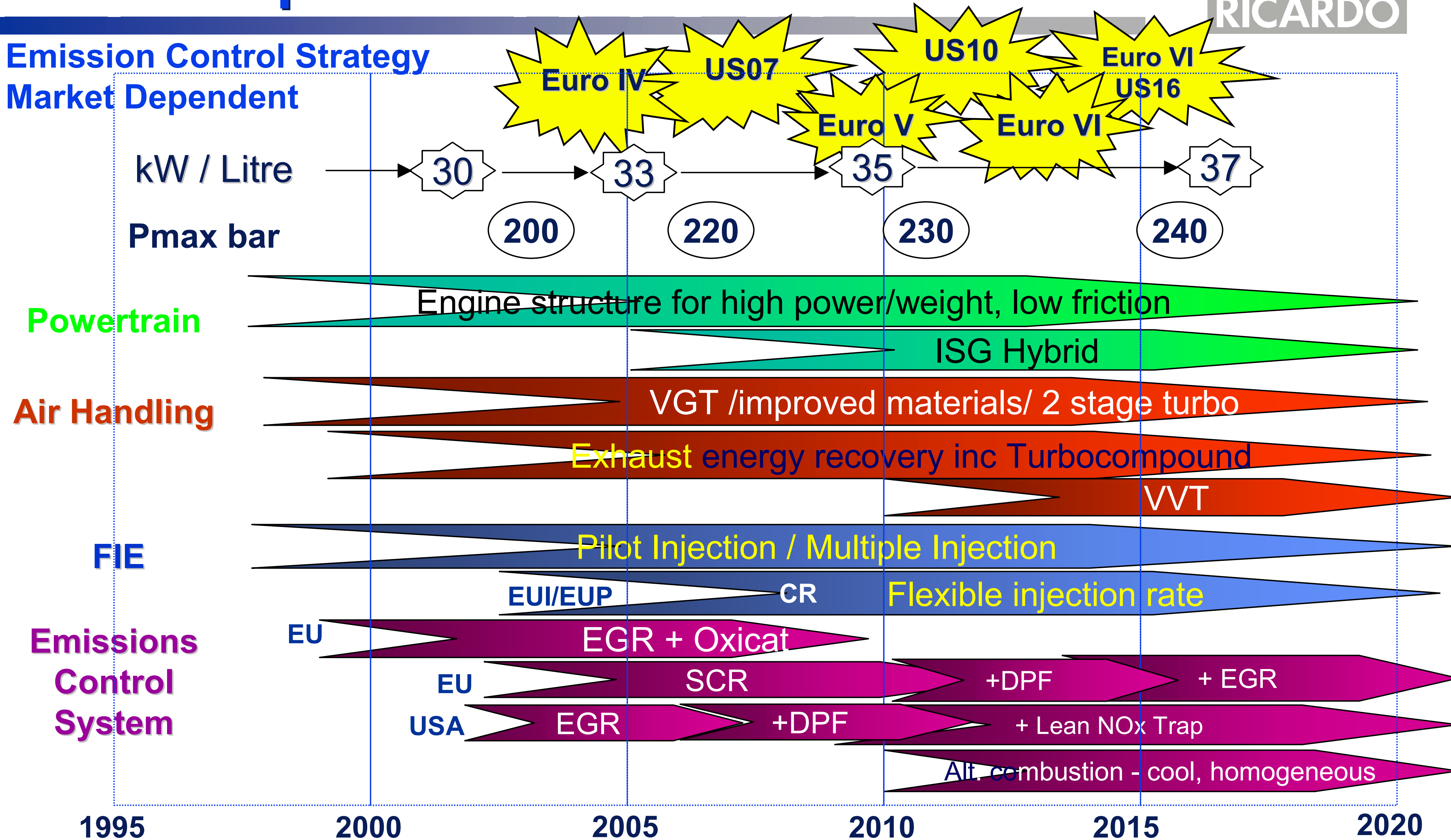
Expected Technology Penetration: Diesel MDT

Year of Introduction	1987	1992	1996	2000	2005	2010	2015
European Standards [g/kW.h]	**Euro 0 = R49**	**Euro 1**	**Euro 2**	**Euro 3**	**Euro 4**	**Euro 5**	**Euro 6**
Emissions Technology Content (Majority of Vehicles)	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	As Euro 3; further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, but SCR may replace EGR in some medium duty engine applications	Difficult to estimate. Increased use of SCR and other aftertreatment. Further updated FIE, with ever more complex control systems
Number of Valves							
2	90	95	50	0	0	0	0
3 or 4	0	5	50	100	100	100	100
Aspiration							
NA	30	20	0	0	0	0	0
TC	30	30	0	0	0	0	0
TCA	40	50	100	100	100	100	100
Energy Recovery Systems							
Turbocompound	0	0	0	0	0	0	0
FUEL INJECTION EQUIPMENT							
Low Press (< 1000 bar) Mechanical FIE	100	2	0	0	0	0	0
High Pressure Mechanical e.g. RP43, RP25	0	50	30	10	0	0	0
HP Rotary FIE	0	38	10	0	0	0	0
Electronic Rotary FIE	0	10	25	5	0	0	0
Common rail FIE	0	0	0	15	50	60	60
EUI/EUP FIE	0	0	35	65	50	40	40
Others (HPI)	0	0	0	5	0	0	0
Advanced EUI/EUP (such as E3)	0	0	0	0	0	0	0
Nozzle Types							
Minisac Nozzles	100	80	75	70	50	20	10
VCO Nozzles	0	20	25	30	50	80	90
Others (HPI)	0	0	0	0	0	0	0
Extrude-honed Nozzles	0	0	0	80	90	90	90
NOx Reduction Technology							
EGR	0	0	0	10	80	60	40
EGR cooler	0	0	0	10	80	60	40
SCR inj system	0	0	0	0	20	40	60
SCR catalyst	0	0	0	0	20	40	60
Lean NOx trap	0	0	0	0	0	0	0
Aftertreatment							
Catalyst - Oxidation	0	0	0	0	20	40	60
Diesel Particulate Filter	0	0	0	0	80	60	40

Heavy Duty Truck Engines

- Technology trends and development similar to medium duty engines
- Similar expectations for future technologies.
- Larger trucks more likely to use Selective Catalytic Reduction (SCR) technology which will require a new infrastructure for Urea
- In addition, currently limited use of turbo-compounding likely to become more popular in future long haul trucks for fuel economy improvement

Heavy Duty Diesel Technology Roadmap



Heavy Duty Diesel Engines: Potential Routes

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Technology	Development Issue	Euro 4 NOx <3.5 g/kWh (Limit)	Euro 5 NOx <2.5 g/kWh (Limit)	US '02/'04 NOx<~2.0g/bhph	US '07 NOx<1.2g/bhph (Fleet Average)	US'10 NOx<0.2g/bhph (Limit)	Japan NST 2004
Cooled EGR + Oxi-cat or DPF	Engine Re-Design: • High Press. FIE • T/C match Transient EGR Control Active DPF Regeneration	Possible to meet emissions targets with DOC, without DPF. Operating costs higher than SCR.	Capable of meeting emissions targets. May not be preferred due to operating costs.	Preferred technology- no additional infrastructure required DPF NOT REQUIRED	Technology capable of approaching 1.2 g/bhp.h NOx. Needs further development. Preferred solution.	EGR unable to meet NOx level. May be used in conjunction with other NOx reduction technologies.	Preferred technology - no additional infrastructure required
SCR or SCR + DPF	Urea: • Infrastructure • Injection control through transients Ammonia Slip Active DPF Regeneration	Preferred for long haul trucks - lowest life cycle costs. DPF probably not required.	Preferred technology. Can recover additional operating costs. DPF may not be required.	Timescale too short. - No urea infrastructure.	US EPA concerned about urea distribution and in use compliance. Now under consideration.	US EPA concerned about urea distribution and in use compliance. Now under consideration.	Infrastructure unlikely to be available. Too complex, costly
LNT + DPF	Rich Spike Calibration for deNOx Sulphur Poisoning / Desulphation Active DPF Regeneration	Not available in time frame. Complex. Sulphur level too high.	Technology not yet proven to be durable. May require dual system. Fuel cons. Penalty. Complex and costly.	Not available in time frame. Complex. Sulphur level too high.	Favoured by US-EPA. Significant technical challenges still to be solved. Durability? Sulphur level?	Favoured by US-EPA. Significant technical challenges still to be solved. Durability? Sulphur level?	Not available in time frame. Complex. Sulphur level?

Expected Technology Penetration: Diesel HDT

Year of Introduction	1987	1992	1996	2000	2005	2010	2015
European Standards [g/kW.h]	Euro 0 = R49	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
Emissions Technology Content (Majority of Vehicles)	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
Number of Valves							
2	90	90	5	0	0	0	0
3 or 4	10	10	95	100	100	100	100
Aspiration							
NA	20	20	0	0	0	0	0
TC	30	30	0	0	0	0	0
TCA	50	50	100	100	100	100	100
Energy Recovery Systems							
Turbocompound	0	0	0	1	2	5	8
FUEL INJECTION EQUIPMENT							
Low Press (< 1000 bar) Mechanical FIE	100	0	0	0	0	0	0
High Pressure Mechanical e.g. RP39	0	90	60	10	0	0	0
HP Rotary FIE	0	5	0	0	0	0	0
Electronic Rotary FIE	0	5	5	2	0	0	0
Common rail FIE	0	0	0	15	30	40	45
EUI/EUP FIE	0	0	35	68	50	10	2
Others (HPI)	0	0	0	5	10	10	8
Advanced EUI/EUP (such as E3)	0	0	0	0	10	40	45
Nozzle Types							
Minisac Nozzles	100	90	90	85	80	80	75
VCO Nozzles	0	10	10	10	10	10	10
Others (HPI)	0	0	0	5	10	10	15
Extrude-honed Nozzles	0	0	0	80	90	90	95
NOx Reduction Technology							
EGR	0	0	0	5	50	25	10
EGR cooler	0	0	0	5	50	25	10
SCR inj system	0	0	0	0	50	60	80
SCR catalyst	0	0	0	0	50	60	80
Lean NOx trap	0	0	0	0	0	5	7
Aftertreatment							
Catalyst - Oxidation	0	0	0	0	25	25	25
Diesel Particulate Filter	0	0	0	0	30	30	30

Contents

- Introduction
- Approach
- Technology selections
- Areas considered for cost
- Key Results
- Example of technologies and costs considered
- Emissions – Regulated
- Emissions - Unregulated
- Conclusions

Components Considered for Cost

- In order to suitably estimate costs of emissions equipment the following steps were taken for each sector (e.g. gasoline car)
  - Identify technologies used or expected to be used ✓
  - Assess their penetration within the market, or that expected in future, for each emissions legislation from 1990 to 2012 ✓
  - Research to estimate material, tooling and development costs for each technology
  - Calculate amortised costs of each technology
  - Sum amortised costs of each technology according to the estimated penetration within the market to get a final cost

Note: Due to the confidential sources used for this study, none of the original cost data is disclosed in this report.

Components Considered for Cost

- Gasoline technologies included the following:
  - Fuel Injection
    - Direct Injection including Lean NOx Trap
    - Single and multi-point injection including Throttle-body
  - Electronic Control System
    - ECU and sensors
    - Electronic Ignition System – including distributor-less systems
  - After treatment
    - Three way catalytic converter – starter &/or close coupled, under floor
    - Lambda sensor – heated and unheated; pre and post catalyst
    - Secondary air system
  - Alternative strategies
    - EGR valve / pipework
    - Evaporative emissions equipment
    - Turbo, ducting and charge cooler where used for engine downsizing
    - Variable cam phasing
    - Mild Hybrid including ISG and 42V battery pack

Components Considered for Cost

- Light Duty Diesel technologies included:
  - Fuel Injection Equipment
    - Rotary pump; direct and indirect
    - Electronic unit injectors (generation 1 and generation 2)
    - Common rail (gen 1 - 1300 bar, gen 2 - 1600 bar, gen 3 - 1800/2000 bar)
  - ECU
  - Air management
    - Naturally aspirated / turbocharger(s) / intercooler / intercooler by-pass
    - 4 valves per cylinder
    - Inlet port deactivation (variable swirl)
    - EGR circuit including EGR cooler and modulated EGR cooling
  - After treatment
    - Diesel oxidation catalyst (s)
    - Diesel particulate filter
    - Lean NOx trap
    - Diesel 4-way catalyst
    - Selective Catalytic Reduction (SCR) - Urea required

Components Considered for Cost

- Medium and Heavy Duty Diesel technology included:
  - Aspiration; incl. normally aspirated, turbocharged, aftercooled
  - Turbocompound
  - Fuel Injection Equipment
    - Intermediate Pressure (< 1000 bar) Mechanical FIE
    - High Pressure (>1000 bar) Mechanical e.g. RP39
    - Electronic Rotary FIE
    - Common rail FIE
    - EUI/EUP FIE
    - Advanced EUI/EUP (such as E3)
    - Nozzle Types including Minisac, VCO, Extrude-honed/hydro-ground
  - EGR
  - Aftertreatment
    - Catalyst – Oxidation (DOC)
    - Diesel Particulate Filter (DPF)
    - Selective Catalytic Reduction (SCR)
    - Lean NOx trap (LNT)

Contents

Key Results

- These are presented for each sector in turn
- Key results are:
  - Cost to build - amortised
  - Cost to maintain - amortised
  - Equipment life expectation
  - Fuel economy change in percent and proportion
    - For light duty vehicles, data is presented from two sources; test results and theoretical expectation (excludes other influences)
  - Regulated emissions in g/km or g/kWh and g.GJ
    - Light duty truck results averaged for LDT1, 2 and 3
    - Percentage reduction in emissions since 1990 given for each
  - Unregulated emissions in g/km or g/kWh and g.GJ
    - Percentage reduction in emissions since 1990 given for each

Key Results - Definition

- Table shows definitions of each parameter

Item	Classification / Parameter	Symbol	Definition
1	Principal Technology Requirement		Main thrust of industry response to legislative demands
2	Investment Costs [Euro]	*I*	Amortized cost/vehicle of components, tooling and development.
3	Additional Operating and Maintenance costs [Euro]	*f*	Amortized cost/vehicle of components, delivery and fitting of failed emissions system parts
5	Lifetime of control Equipment [years]	*lt*	Expected system life
9	Change in engine fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	Percentage change in engine specific fuel consumption relative to 1990 baseline due only to emission reduction technology
10	Average vehicle fuel consumption 2005-2010 relative to 1990 [fraction]	*fe*	Percentage change in vehicle fuel consumption relative to 1990 baseline taking all factors into account
11.01	Tail pipe CO / HC / NOx / PM emissions [g/km]		Based on urban drive cycle
11.02	Efficiency of Euro (?) CO / HC / NOx / PM, etc measures [%]		Relative to 1990 baseline or first non-zero value
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	From internal sources (including but not limited to drive cycle)
13	Efficiency of Euro (?) PM2.5 measures [%]	$\eta_{PM2.5}$	Relative to 1990 baseline or first non-zero value
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	From internal sources (including but not limited to drive cycle)
16	Tail pipe N_2O emission factor [g/km]	ef_{NOx}	From internal sources (including but not limited to drive cycle)
18	Tail pipe VOC emission factor [g/km]	ef_{VOC}	From internal sources (including but not limited to drive cycle)
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	From internal sources, based on change in fuel sulphur levels
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	From internal sources (including but not limited to drive cycle)

- Fuel data used to convert to g/GJ is quoted for each fuel. These values are supplied by CITEPA and are in line with those used by IIASA

Key Results - Conversion from g/X to g/GJ

- g/km to g/GJ:

$$Value(g/GJ) = \frac{Value(g/km)}{\left[\frac{Fuel\_economy(l/100km)}{100(km)}\right](l/km) x \rho_{fuel}(kg/l) x NCV_{fuel}(GJ/kg)}$$

- g/kWh to g/GJ:

$$Value(g/GJ) = Value(g/kW.h) x \frac{Fuel\_efficiency(factor)}{0.0036(gJ/kWh)}$$

Where:

$$Fuel\_efficiency(factor) = \frac{0.0036(GJ/kW.h) / Fuel\_economy(g/kWh)}{NCV_{fuel}(GJ/kg) / 1000(g/kg)}$$

Key Results: Gasoline Car Technology Development

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Item		Euro Emissions Legislation / Year of introduction						
		0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**	Carburettor / Single Point Injection with Distributor Ignition or Limited use of electronic control	3-way catalyst with lambda sensor, electronic injection, electronic ignition, and basic evaporative emissions equipment	3-way catalyst with lambda sensor, electronic injection, electronic ignition and basic evaporative emissions equipment with: Better hardware design, higher catalyst loading, some use of EGR, more widespread use of multi-point injection	3-way catalyst with lambda sensor, electronic injection, electronic ignition and better hardware design, some use of EGR, more widespread use of multi-point injection: Post catalyst O2 sensor, revised controller and software, further increased catalyst loading, full evaporative emissions equipment, actions for reduced base engine friction	Suitably loaded 3-way catalyst with lambda sensor, electronic injection, electronic ignition and better hardware design, mostly multi-point injection, post catalyst O2 sensor, revised controller and software, full evaporative emissions equipment, actions for reduced base engine friction, plus: Starter (pup) cat with revised high speed fuelling strategy (keep cat cool), increased use of EGR or variable cam phasing	3-way catalyst with lambda sensor, electronic injection, electronic ignition and better hardware design, more widespread use of multi-point injection, post catalyst O2 sensor, revised controller and software, further increased catalyst loading, full evaporative emissions equipment, actions for reduced base engine friction, starter cat with revised high speed fuelling strategy, EGR or more commonly variable cam phasing. Also use of lean burn direct Injection	3-way catalyst with lambda sensor, electronic injection and ignition, better hardware design, more widespread use of multi-point injection, post catalyst O2 sensor, enhanced controller and software, further increased catalyst loading, full evaporative emissions equipment, actions for reduced base engine friction, starter cat with revised high speed fuelling strategy, variable cam phasing common. Increased use of lean burn direct injection, boosted downsized engines, or hybrid technology

- Only additional technologies are shown in line item 1 of later graphs

Key Results: Gasoline Car Cost and Fuel Economy

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Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		R [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
	Assumptions			Engine built at 100,000 units per annum - no premium paid for low volumes						
2	Investment Costs [Euro]	*I*	R	0	262	269	341	382	445	585
3	Additional Operating and Maintenance costs [Euro]	*f*	R	0	140	103	123	105	125	155
5	Lifetime of control Equipment [years]	*lt*	R	6	6	8	8	10	10	10
9	Change in fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	R [3]	100	104	101	99	98	95	90
10	Average fuel consumption 2005-2010 relative to 1990 [fraction]	*fe*	R	1.000	1.025	1.149	1.130	1.096	1.060	1.000

- Control equipment life based on requirement plus engineering margin
- Maintenance costs estimated over 150,000km (emissions system only)
- Line 9 based on known effect of individual emissions reduction measures
- Line 10 based on averaged fuel economy results

Key Results: Gasoline Car Emissions

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		R [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
11.01	Tail pipe CO emissions [g/km]			9.06	0.68	0.65	0.75	0.48	0.45	0.45
11.02	Efficiency of Euro (?) CO measures [%]			0	92	93	92	95	95	95
11.03	Tail pipe HC emissions [g/km]			2.024	0.165	0.100	0.088	0.065	0.06	0.06
11.04	Efficiency of Euro (?) HC measures [%]			0	92	95	96	97	97	97
11.05	Tail pipe HC + NOx emissions [g/km]			3.68	0.35	0.207	0.028	0.098	0.085	0.09
11.06	Efficiency of Euro (?) HC +NOx measures [%]			0	91	94	99	97	98	98
11.07	Tail pipe NOx emissions [g/km]			1.66	0.185	0.1066	0.053	0.033	0.025	0.03
11.08	Efficiency of Euro (?) NOx measures [%]			0	89	94	97	98	98	98
11.09	Tail pipe PM emissions [g/km]			*0.075*	*0.04*	*0.02*	0.004	0.004	0.007	0.008
11.10	Efficiency of Euro (?) PM measures [%]			0	47	73	95	95	91	89

- No PM measurements before MY 2000 – blue italics indicate low confidence
- Future PM emissions will depend upon direct injection technology
  - Assumed to be 30% penetration by 2012

Key Results: Gasoline Car Emissions

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		**R** [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
11.51	Tail pipe CO emissions [g/GJ]			**3778**	**277**	**235**	**277**	**182**	**177**	**183**
11.52	Efficiency of Euro (?) CO measures [%]			**0**	**93**	**94**	**93**	**95**	**95**	**95**
11.53	Tail pipe HC emissions [g/GJ]			**844**	**67**	**36**	**32**	**25**	**24**	**24**
11.54	Efficiency of Euro (?) HC measures [%]			**0**	**92**	**96**	**96**	**97**	**97**	**97**
11.55	Tail pipe HC + NOx emissions [g/GJ]			**1537**	**142**	**75**	**10**	**37**	**33**	**37**
11.56	Efficiency of Euro (?) HC +NOx measures [%]			**0**	**91**	**95**	**99**	**98**	**98**	**98**
11.57	Tail pipe NOx emissions [g/GJ]			**693**	**75**	**39**	**20**	**13**	**10**	**12**
11.58	Efficiency of Euro (?) NOx measures [%]			**0**	**89**	**94**	**97**	**98**	**99**	**98**
11.59	Tail pipe PM emissions [g/GJ]			***31***	***16***	***7***	**1.5**	**1.5**	**2.8**	**3.3**
11.60	Efficiency of Euro (?) PM measures [%]			**0**	**48**	**77**	**95**	**95**	**91**	**90**

- Data presented g/GJ Fuel
  - Fuel density = 760 kg/m3; Gross Calorific Value = 44.77 MJ/kg
  - Combined Cycle Fuel Economy used for calculations

Key Results: Gasoline Car Unregulated Emissions – g/km

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		R [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	R [4]	*0.0264*	*0.0088*	0.0035	0.0044	0.0048	0.0057	0.0070
13	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	0	67	87	83	82	78	73
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	R [4]	*0.03*	*0.01*	0.0040	0.0050	0.0055	0.0065	0.008
15	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	0	67	87	83	82	78	73
16	Tail pipe N_2O emission factor [g/km]	ef_{N2O}	R [4]	0	0	0.024	0.0018	0.002	0.003	0.0035
17	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	-	-	0	93	92	88	85
18	Tail pipe VOC emission factor [g/km]	ef_{VOC}	R [4]							
	1,3 Butadiene			0.01	0.005	0.0044	0.0017	0.0013	0.0012	0.0012
	Benzene			0.08	0.04	0.004	0.004	0.001	0.005	0.005
	Formaldehyde			0.005	0.003	0.014	0.0001	0.0001	0.0001	0.0001
	Acetaldehyde			0.002	0.001	0	0	0	0	0
19	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	49	77	94	98	94	94
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	R [4]	0.0075	0.007	0.0026	0.0009	0.00075	0.00072	0.00068
21	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	7	65	88	90	90	91
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	R [4]	0	0	0.017	0.0038	0.004	0.005	0.0055
23	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	78	76	71	68

- Blue italics indicate poor confidence in data supplied

Key Results: Gasoline Car Unregulated Emissions – g/GJ

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		R [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
12.5	Tail pipe PM2.5 emissions factor [g/GJ]	$ef_{PM2.5}$	R [4]	*11.0*	*3.6*	1.3	1.6	1.84	2.3	2.9
13.5	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	0	67	88	85	83	80	73
14.5	Tail pipe PM10 emission factor [g/GJ]	ef_{PM10}	R [4]	*12.5*	*4.1*	1.4	1.9	2.1	2.6	3.3
15.5	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	0	67	88	85	83	80	73
16.5	Tail pipe N_2O emission factor [g/GJ]	ef_{N2O}	R [4]	0	0	8.7	0.7	0.8	1.2	1.5
17.5	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	-	-	0	92	91	86	83
18.5	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	R [4]							
	1,3 Butadiene			4.17	2.04	1.60	0.63	0.48	0.46	0.48
	Benzene			33.37	16.28	1.45	1.48	0.38	1.97	2.09
	Formaldehyde			2.09	1.22	5.08	0.04	0.04	0.04	0.04
	Acetaldehyde			0.83	0.41	0.00	0.00	0.00	0.00	0.00
19.5	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	51	80	95	98	94	94
20.5	Tail pipe SO2 emission factor [g/GJ]	ef_{SO2}	R [4]	3.13	2.85	0.96	0.33	0.29	0.28	0.28
21.5	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	9	69	89	91	91	91
22.5	Tail pipe NH3 emission factor [g/GJ]	ef_{NH3}	R [4]	0	0	6.17	1.40	1.52	1.97	2.29
23.5	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	77	75	68	63

- Blue italics indicate poor confidence in data supplied

Key Results: Gasoline Car Discussion

- Fuel economy drop at Euro 1 is a result of needing richer air/fuel ratios to maintain catalyst efficiency
- On-costs relative to the Euro 0 baseline, not incremental
- On-cost increased for later emissions legislation in part due to increased use of direct injection and to a lesser extent hybrid technology
- Factors included in estimating maintenance costs are
  - Most systems become more reliable with time so maintenance costs of existing technologies tend to drop – particularly true with electronic systems
  - Improved detection of failures by OBD systems
  - No attempt to estimate costs to dealer specifically resulting from emissions requirements
    - Usually incorporated into labour costs – estimations of these are included
- Emissions data based on an average of several vehicles, average displacement of ~1700cc
- Engineering judgement used where no data available

Key Results: Gasoline LDT Technology Development

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Item		Euro Emissions Legislation / Year of introduction						
		0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**	Carburettor / Single Point Injection with Distributor Ignition or Limited use of electronic control	3-way catalyst with lambda sensor, electronic injection, electronic ignition, and basic evaporative emissions equipment	3-way catalyst with lambda sensor, electronic injection, electronic ignition and basic evaporative emissions equipment with: Better hardware design, higher catalyst loading, some use of EGR, more widespread use of multi-point injection	3-way catalyst with lambda sensor, electronic injection, electronic ignition and better hardware design, some use of EGR, more widespread use of multi-point injection: Post catalyst O2 sensor, revised controller and software, further increased catalyst loading, full evaporative emissions equipment, actions for reduced base engine friction	Suitably loaded 3-way catalyst with lambda sensor, electronic injection, electronic ignition and better hardware design, mostly multi-point injection, post catalyst O2 sensor, revised controller and software, full evaporative emissions equipment, actions for reduced base engine friction, plus: Starter (pup) cat with revised high speed fuelling strategy (keep cat cool), increased use of EGR or variable cam phasing	3-way catalyst with lambda sensor, electronic injection, electronic ignition and better hardware design, more widespread use of multi-point injection, post catalyst O2 sensor, revised controller and software, further increased catalyst loading, full evaporative emissions equipment, actions for reduced base engine friction, starter cat with revised high speed fuelling strategy, EGR or more commonly variable cam phasing. Also use of lean burn direct Injection	3-way catalyst with lambda sensor, electronic injection and ignition, better hardware design, more widespread use of multi-point injection, post catalyst O2 sensor, enhanced controller and software, further increased catalyst loading, full evaporative emissions equipment, actions for reduced base engine friction, starter cat with revised high speed fuelling strategy, variable cam phasing common. Increased use of lean burn direct Injection or boosted downsized engines

- Only additional technologies are shown in line item 1 of later graphs

Key Results: Gasoline LDT Costs and Fuel Economy

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
	Assumptions		Engine built at 100,000 units per annum - no premium paid for low volumes						
2	Investment Costs [Euro]	I	**0**	**283**	**286**	**354**	**375**	**402**	**453**
3	Additional Operating and Maintenance costs [Euro]	f	**0**	**220**	**183**	**170**	**125**	**126**	**120**
5	Lifetime of control Equipment [years]	lt	**6**	**6**	**8**	**8**	**10**	**10**	**10**
9	Change in fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	**100**	**100**	**98**	**97**	**96**	**95**	**94**
10	Average fuel consumption 2005-2010 relative to 1990 [fraction]	fe	**1.000**	**0.923**	**0.895**	**0.881**	**0.853**	**0.831**	**0.809**

- Maintenance costs estimated over estimated vehicle life of 175,000 km
- Assumes that technology such as lean direct injection will be used less in LDT than in passenger car

Key Results: Gasoline LDT Emissions

RICARDO

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
11.10	Tail pipe CO emissions [g/km]		10.91	1.42	1.37	1.25	1.12	1.08	1.08
11.15	Efficiency of Euro (?) CO measures [%]		0	87	87	89	90	90	90
11.20	Tail pipe HC emissions [g/km]		1.765	0.19	0.17	0.115	0.108	0.102	0.108
11.25	Efficiency of Euro (?) HC measures [%]		0	89	90	93	94	94	97
11.30	Tail pipe HC + NOx emissions [g/km]		3.96	0.4	0.310	0.171	0.148	0.137	0.138
11.35	Efficiency of Euro (?) HC +NOx measures [%]		0	90	92	96	96	97	97
11.40	Tail pipe NOx emissions [g/km]		2.19	0.21	0.14	0.056	0.040	0.035	0.03
11.45	Efficiency of Euro (?) NOx measures [%]		0	90	94	97	98	98	99
11.50	Tail pipe PM emissions [g/km]		*22*	*7*	*2*	0.005	0.005	0.005	0.006
11.55	Efficiency of Euro (?) PM measures [%]		0	68	91	100	100	100	100

- Data collected for a sample representing LDT 1, 2 and 3
- Data in blue italics presented with low degree of confidence

Key Results: Gasoline LDT Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
11.10	Tail pipe CO emissions [g/GJ]		**3027**	**427**	**425**	**394**	**364**	**361**	**367**
11.15	Efficiency of Euro (?) CO measures [%]		**0**	**86**	**86**	**87**	**88**	**88**	**88**
11.20	Tail pipe HC emissions [g/GJ]		**490**	**57**	**53**	**36**	**35**	**34**	**37**
11.25	Efficiency of Euro (?) HC measures [%]		**0**	**88**	**89**	**93**	**93**	**93**	**93**
11.30	Tail pipe HC + NOx emissions [g/GJ]		**1098**	**120**	**96**	**54**	**48**	**46**	**47**
11.35	Efficiency of Euro (?) HC +NOx measures [%]		**0**	**89**	**91**	**95**	**96**	**96**	**96**
11.40	Tail pipe NOx emissions [g/GJ]		**608**	**63**	**43**	**18**	**13**	**12**	**10**
11.45	Efficiency of Euro (?) NOx measures [%]		**0**	**90**	**93**	**97**	**98**	**98**	**98**
11.50	Tail pipe PM emissions [g/GJ]		***6104***	***2104***	***620***	**1.6**	**1.6**	**1.7**	**2.0**
11.55	Efficiency of Euro (?) PM measures [%]		**0**	**66**	**90**	**100**	**100**	**100**	**100**

- Blue italics indicate poor confidence in data supplied
- Data presented g/GJ Fuel, based on Combined cycle fuel economy
  - Fuel density = 760 kg/m3; Gross Calorific Value = 44.77 MJ/kg

Key Results: Gasoline LDT Unregulated Emissions – g/km

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		R [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	R [4]	*0.0396*	*0.01408*	0.0051	0.0064	0.0065	0.0066	0.0070
13	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	0	64	87.20777778	84	84	83	82
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	R [4]	*0.045*	*0.016*	0.0058	0.0073	0.0074	0.0075	0.0080
15	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	0	64	87	84	84	83	82
16	Tail pipe N_2O emission factor [g/km]	ef_{N2O}	R [4]	0	0	0.024	0.0018	0.002	0.003	0.0035
17	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	-	-	0	93	92	88	85
18	Tail pipe VOC emission factor [g/km]	ef_{VOC}	R [4]							
	1,3 Butadiene			0.01	0.005	0.0044	0.0017	0.0016	0.0015	0.0016
	Benzene			0.08	0.04	0.004	0.004	0.001	0.005	0.005
	Formaldehyde			0.005	0.003	0.014	0.0001	0.0001	0.0001	0.0001
	Acetaldehyde			0.002	0.001	0	0	0	0	0
19	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	49	77	94	97	93	93
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	R [4]	0.0113	0.0095	0.0031	0.0011	0.0009	0.0008	0.0008
21	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	16	73	91	92	92	93
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	R [4]	0	0	0.017	0.0038	0.004	0.005	0.0055
23	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	78	76	71	68

- Blue italics indicate poor confidence in data supplied

Key Results: Gasoline LDT Unregulated Emissions – g/GJ

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Principal Technology Requirement**		R [1]	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines
12.5	Tail pipe PM2.5 emissions factor [g/GJ]	$ef_{PM2.5}$	R [4]	*11.0*	*4.23*	1.57	2.02	2.12	2.22	2.38
13.5	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	0	61	86	82	81	80	78
14.5	Tail pipe PM10 emission factor [g/GJ]	ef_{PM10}	R [4]	*12.5*	*4.8*	1.78	2.29	2.40	2.52	2.71
15.5	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	0	61	86	82	81	80	78
16.5	Tail pipe N_2O emission factor [g/GJ]	ef_{N2O}	R [4]	0	0	7.44	0.57	0.65	1.00	1.19
17.5	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	-	-	0	92	91	87	84
18.5	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	R [4]							
	1,3 Butadiene			2.77	1.50	1.36	0.54	0.52	0.50	0.54
	Benzene			22.20	12.02	1.24	1.26	0.33	1.67	1.70
	Formaldehyde			1.39	0.90	4.34	0.03	0.03	0.03	0.03
	Acetaldehyde			0.55	0.30	0.00	0.00	0.00	0.00	0.00
19.5	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	45	74	93	97	92	92
20.5	Tail pipe SO2 emission factor [g/GJ]	ef_{SO2}	R [4]	3.13	2.85	0.96	0.33	0.29	0.28	0.28
21.5	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	9	69	89	91	91	91
22.5	Tail pipe NH3 emission factor [g/GJ]	ef_{NH3}	R [4]	0	0	5.27	1.20	1.30	1.67	1.87
23.5	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	77	75	68	65

- Blue italics indicate poor confidence in data supplied

Key Results: Gasoline LDT Discussion

- Initial on-cost similar to gasoline cars
- Maintenance costs expected to continue to fall owing to limited use of new technology
  - Penetration of direct injection expected to be low, this has led to a continuation of trends of both cost and emissions for Euro 5 and Euro 6
- Unlike gasoline cars, fuel economy seen to fall throughout
  - Likely that carburetted vans were tuned to run slightly richer than cars
  - Engine loading different
  - Vehicle mass not subject to increases seen in cars
  - Technology content generally lower in LDT engines than in passenger car engines

Key Results: Diesel Car Technology Development

RICARDO

Item		Euro Emissions Legislation / Year of introduction						
		0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Electronic control DI fuel pump, DI combustion system, high pressure injectors plus: Turbocharger to reduce displacement	Electronic control DI fuel pump, DI combustion system, high pressure injectors, turbocharger to reduce displacement plus: 4 valve per cylinder (revised combustion characteristics)	DI combustion system, high pressure injectors, turbocharger to reduce displacement, 4 valve per cylinder (revised combustion characteristics) plus: Common rail system to replace electronically controlled distributor pump	DI combustion system, high pressure injectors, turbocharger to reduce displacement, 4 valve per cylinder (revised combustion characteristics), common rail system to replace electronically controlled distributor pump plus: Port deactivation, Diesel Particulate Filter (DPF), NOx Aftertreatment? (2010)	DI combustion system, turbocharger to reduce displacement, 4 valve per cylinder (revised combustion characteristics), common rail system to replace electronically controlled distributor pump, port deactivation, plus: Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls

- ❑ Only additional technologies are shown in line item 1 of later graphs

Key Results: Diesel Car Cost and Fuel Economy

RICARDO

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
	Assumptions		Initial cost of engine (no emissions control equipment) = €600						
2	Investment Costs [Euro]	*I*	**0**	**78**	**47**	**129**	**267**	**440**	**520**
3	Additional Operating and Maintenance costs [Euro]	*f*	**0**	**125**	**118**	**120**	**132**	**145**	**165**
5	Lifetime of control Equipment [years]	*lt*	**10**	**10**	**10**	**10**	**10**	**10**	**10**
9	Change in fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	**100**	**92**	**87**	**82**	**84**	**86**	**87**
10	Average fuel consumption 2005-2010 relative to 1990 [fraction]	*fe*	**1.000**	**1.006**	**1.168**	**1.063**	**1.040**	**1.006**	**1.020**

- Maintenance costs estimated for 200,000km (emissions system only)
- Line 9 based on known effect of individual emissions reduction measures
- Line 10 based on averaged fuel economy results

Key Results: Diesel Car Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
11.01	Tail pipe CO emissions [g/km]		1.146	0.850	0.458	0.208	0.2	0.35	0.3
11.02	Efficiency of Euro (?) CO measures [%]		0	26	60	82	83	69	74
11.03	Tail pipe HC emissions [g/km]		0.281	0.12	0.07	0.04	0.06	0.07	0.07
11.04	Efficiency of Euro (?) HC measures [%]		0	57	75	87	79	75	75
11.05	Tail pipe HC + NOx emissions [g/km]		1.230	0.71	0.596	0.438	0.24	0.135	0.12
11.06	Efficiency of Euro (?) HC +NOx measures [%]		0	42	52	64	80	89	90
11.07	Tail pipe NOx emissions [g/km]		0.949	0.590	0.526	0.402	0.20	0.065	0.05
11.08	Efficiency of Euro (?) NOx measures [%]		0	38	45	58	79	93	95
11.09	Tail pipe PM emissions [g/km]		0.147	0.11	0.062	0.032	0.018	0.002	0.0015
11.10	Efficiency of Euro (?) PM measures [%]		0	25	58	78	88	99	99

- Measurements in g/km

Key Results: Diesel Car Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
11.51	Tail pipe CO emissions [g/GJ]		**601**	**443**	**206**	**104**	**101**	**182**	**154**
11.52	Efficiency of Euro (?) CO measures [%]		**0**	**26**	**66**	**83**	**83**	**70**	**74**
11.53	Tail pipe HC emissions [g/GJ]		**147**	**62**	**31**	**18**	**30**	**36**	**36**
11.54	Efficiency of Euro (?) HC measures [%]		**0**	**58**	**79**	**88**	**79**	**75**	**76**
11.55	Tail pipe HC + NOx emissions [g/GJ]		**645**	**370**	**267**	**218**	**121**	**70**	**62**
11.56	Efficiency of Euro (?) HC +NOx measures [%]		**0**	**43**	**59**	**66**	**81**	**89**	**90**
11.57	Tail pipe NOx emissions [g/GJ]		**497**	**307**	**236**	**200**	**101**	**34**	**26**
11.58	Efficiency of Euro (?) NOx measures [%]		**0**	**38**	**53**	**60**	**80**	**93**	**95**
11.59	Tail pipe PM emissions [g/GJ]		**77**	**57**	**28**	**16**	**9**	**1**	**1**
11.60	Efficiency of Euro (?) PM measures [%]		**-**	**25**	**64**	**79**	**88**	**99**	**99**

- Data presented g/GJ Fuel, based on Combine cycle fuel economy
  - Fuel density = 860 kg/m3; Gross Calorific Value = 43.3 MJ/kg

Key Results: Diesel Car Unregulated Emissions – g/km

RICARDO

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		R [1]	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	R [4]	0.150	0.034	0.020	0.012	0.010	0.004	0.004
13	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	0	77	86	92	93	97	97
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	R [4]	0.171	0.039	0.023	0.014	0.011	0.005	0.005
15	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	0	77	86	92	93	97	97
16	Tail pipe N_2O emission factor [g/km]	ef_{N2O}	R [4]	0	0	0.0048	0.0035	0.0035	0.01	0.015
17	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	-	-	0	27	27	-108	-213
18	Tail pipe VOC emission factor [g/km]	ef_{VOC}	R [4]							
	1,3 Butadiene			0.004	0.004	0.0047	0.0014	0.001	0.001	0.001
	Benzene			0.003	0.003	0.001	0.001	0.001	0.002	0.002
	Formaldehyde			0.025	0.02	0.0109	0.0017	0.001	0.001	0.001
	Acetaldehyde			0.01	0.01	0.0044	0.0021	0.002	0.002	0.002
19	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	12	50	85	88	86	86
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	R [4]	0.0118	0.0119	0.0034	0.0014	0.0002	0.0002	0.0002
21	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	-1	71	88	98	98	98
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	R [4]	0	0	0.0077	0.0034	0.0034	0.02	0.025
23	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	56	56	-160	-225

Key Results: Diesel Car Unregulated Emissions – g/GJ

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		R [1]	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
12.5	Tail pipe PM2.5 emissions factor [g/GJ]	$ef_{PM2.5}$	R [4]	78.4	17.9	9.2	6.1	5.0	2.3	2.1
13.5	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	-	77	88	92	94	97	97
14.5	Tail pipe PM10 emission factor [g/GJ]	ef_{PM10}	R [4]	89.6	20.5	10.5	7.0	5.8	2.6	2.6
15.5	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	-	77	88	92	94	97	97
16.5	Tail pipe N_2O emission factor [g/GJ]	ef_{N2O}	R [4]	0	0	2.2	1.7	1.8	5.2	7.7
17.5	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	-	-	0	19	18	-142	-258
18.5	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	R [4]							
	1,3 Butadiene			2.10	2.08	2.11	0.70	0.50	0.52	0.51
	Benzene			1.57	1.56	0.45	0.50	0.50	1.04	1.03
	Formaldehyde			13.10	10.42	4.89	0.85	0.50	0.52	0.51
	Acetaldehyde			5.24	5.21	1.97	1.05	1.01	1.04	1.03
19.5	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	12	57	86	89	86	86
20.5	Tail pipe SO2 emission factor [g/GJ]	ef_{SO2}	R [4]	6.20	6.20	1.53	0.70	0.10	0.10	0.10
21.5	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	0	75	89	98	98	98
22.5	Tail pipe NH3 emission factor [g/GJ]	ef_{NH3}	R [4]	0	0	3.45	1.70	1.71	10.42	12.85
23.5	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	51	50	-202	-272

Key Results: Diesel Car Discussion

- Increase in fuel consumption for Euro 2 emissions
  - Increased vehicle mass a significant contributor
  - Reduced NOx requirement achieved by retarding injection timing, thus reducing engine efficiency
- Emissions calibrated to be within a safe margin but PM and NOx tend to be the limiting factors, leaving other emissions levels at a greater margin of safety
- General upward trend in maintenance cost
  - Maintenance costs seen to fall for Euro 3 as electronic fuel pump better established; expected to experience improved reliability
- Expected lifetime = 10 years throughout
  - Expectation by engineers that component life would be at least as long as vehicle life
  - Maintenance cost slightly higher than gasoline as the higher repair costs more than offset the increased reliability of diesel engines

Key Results: Diesel LDT Technology Development

RICARDO

Item		Euro Emissions Legislation / Year of introduction						
		0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Electronic control DI fuel pump, DI combustion system, high pressure injectors plus: Turbocharger to reduce displacement	Electronic control DI fuel pump, DI combustion system, high pressure injectors, turbocharger to reduce displacement plus: 4 valve per cylinder (revised combustion characteristics)	DI combustion system, high pressure injectors, turbocharger to reduce displacement, 4 valve per cylinder (revised combustion characteristics) plus: Common rail system to replace electronically controlled distributor pump	DI combustion system, high pressure injectors, turbocharger to reduce displacement, 4 valve per cylinder (revised combustion characteristics), common rail system to replace electronically controlled distributor pump plus: Port deactivation, Diesel Particulate Filter (DPF), NOx Aftertreatment? (2010)	DI combustion system, turbocharger to reduce displacement, 4 valve per cylinder (revised combustion characteristics), common rail system to replace electronically controlled distributor pump, port deactivation, plus: Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls

- Only additional technologies are shown in line item 1 of later graphs

Key Results: Diesel LDT Cost and Fuel Economy

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
	Assumptions		Initial cost of engine (no emissions control equipment) = €600						
2	Investment Costs [Euro]	*I*	**0**	**78**	**47**	**129**	**267**	**440**	**530**
3	Additional Operating and Maintenance costs [Eu	*f*	**0**	**167**	**155**	**162**	**180**	**200**	**235**
5	Lifetime of control Equipment [years]	*lt*	**10**	**10**	**10**	**10**	**10**	**10**	**10**
9	Change in fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	**100**	**92**	**87**	**82**	**84**	**86**	**88**
10	Average fuel consumption 2005-2010 relative to 1990 [fraction]	*fe*	**1**	**0.94**	**1.14**	**1.08**	**1.03**	**1.01**	**1.03**

- Maintenance costs estimated for 240,000km (emissions system only)

Key Results: Diesel LDT Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
11.01	Tail pipe CO emissions [g/km]		**0.956**	**0.75**	**0.558**	**0.410**	**0.38**	**0.45**	**0.42**
11.02	Efficiency of Euro (?) CO measures [%]		**0**	**22**	**42**	**57**	**60**	**53**	**56**
11.03	Tail pipe HC emissions [g/km]		**0.212**	**0.11**	**0.07**	**0.048**	**0.060**	**0.08**	**0.08**
11.04	Efficiency of Euro (?) HC measures [%]		**0**	**48**	**67**	**77**	**72**	**62**	**62**
11.05	Tail pipe HC + NOx emissions [g/km]		**1.236**	**1.05**	**0.879**	**0.698**	**0.29**	**0.15**	**0.14**
11.06	Efficiency of Euro (?) HC +NOx measures [%]		**0**	**15**	**29**	**44**	**77**	**88**	**89**
11.07	Tail pipe NOx emissions [g/km]		**1.025**	**0.940**	**0.809**	**0.649**	**0.23**	**0.07**	**0.06**
11.08	Efficiency of Euro (?) NOx measures [%]		**0**	**8**	**21**	**37**	**78**	**93**	**94**
11.09	Tail pipe PM emissions [g/km]		**0.128**	**0.095**	**0.078**	**0.066**	**0.031**	**0.002**	**0.0015**
11.10	Efficiency of Euro (?) PM measures [%]		**0**	**26**	**39**	**49**	**76**	**98**	**99**

- Values in g/km

Key Results: Diesel LDT Emissions

RICARDO

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
11.51	Tail pipe CO emissions [g/GJ]		**382**	**318**	**196**	**151**	**148**	**178**	**163**
11.52	Efficiency of Euro (?) CO measures [%]		**0**	**17**	**49**	**60**	**61**	**53**	**57**
11.53	Tail pipe HC emissions [g/GJ]		**85**	**47**	**25**	**18**	**23**	**32**	**31**
11.54	Efficiency of Euro (?) HC measures [%]		**0**	**45**	**71**	**79**	**72**	**63**	**63**
11.55	Tail pipe HC + NOx emissions [g/GJ]		**495**	**445**	**310**	**258**	**113**	**60**	**54**
11.56	Efficiency of Euro (?) HC +NOx measures [%]		**0**	**10**	**37**	**48**	**77**	**88**	**89**
11.57	Tail pipe NOx emissions [g/GJ]		**410**	**399**	**285**	**240**	**89**	**28**	**23**
11.58	Efficiency of Euro (?) NOx measures [%]		**0**	**3**	**30**	**41**	**78**	**93**	**94**
11.59	Tail pipe PM emissions [g/GJ]		**51**	**40**	**28**	**24**	**12**	**1**	**1**
11.60	Efficiency of Euro (?) PM measures [%]		**-**	**22**	**46**	**53**	**77**	**98**	**99**

- Values in g/GJ Fuel, based on Combined cycle fuel economy
  - Fuel density = 860 kg/m3; Gross Calorific Value = 43.3 MJ/kg

Key Results: Diesel LDT Unregulated Emissions – g/km

RICARDO

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		R [1]	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	R [4]	0.320	0.099	0.059	0.036	0.029	0.004	0.004
13	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	0	69	82	89	91	99	99
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	R [4]	0.366	0.113	0.068	0.041	0.033	0.005	0.005
15	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	0	69	82	89	91	99	99
16	Tail pipe N_2O emission factor [g/km]	ef_{NOx}	R [4]	0	0	0.0061	0.0047	0.0046	0.012	0.01
17	Efficiency of Euro (?) N_2O measures	h_{NOx}	R [4]	-	-	0	24	25	-96	-64
18	Tail pipe VOC emission factor [g/km]	ef_{VOC}	R [4]							
	1,3 Butadiene			0.003	0.0037	0.0047	0.0019	0.001	0.001	0.001
	Benzene			0.0023	0.0028	0.001	0.0013	0.001	0.0023	0.0023
	Formaldehyde			0.0188	0.0183	0.0109	0.0023	0.001	0.001	0.001
	Acetaldehyde			0.0075	0.0092	0.0044	0.0028	0.002	0.0023	0.0023
19	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	0	-7	34	74	84	78	78
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	R [4]	0.0138	0.0129	0.0038	0.0019	0.0003	0.0003	0.0003
21	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	0	6	72	86	98	98	98
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	R [4]	0	0	0.0098	0.0045	0.0044	0.026	0.029
23	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	-	-	0	54	55	-168	-196

Key Results: Diesel LDT Unregulated Emissions – g/GJ

Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		**R [1]**	Mechanical fuel pump / IDI combustion system / Low pressure injectors	Electronic control DI fuel pump / DI combustion system / high pressure injectors	Turbocharger to reduce displacement	4 valve per cylinder	Common rail	Port deactivation Diesel Particulate Filter (DPF) + NOx Aftertreatment ? (2010)	Fully developed aftertreatment strategies allowing better engine optimization for fuel economy. Updated FIE and controls
12.5	Tail pipe PM2.5 emissions factor [g/GJ]	$ef_{PM2.5}$	**R [4]**	**128.1**	**41.9**	**20.9**	**13.1**	**11.3**	**1.7**	**1.7**
13.5	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	**R [4]**	**-**	**67**	**84**	**90**	**91**	**99**	**99**
14.5	Tail pipe PM10 emission factor [g/GJ]	ef_{PM10}	**R [4]**	**146.4**	**47.9**	**23.8**	**15.0**	**12.9**	**2.0**	**1.9**
15.5	Efficiency of Euro (?) PM10 measures	h_{PM10}	**R [4]**	**-**	**67**	**84**	**90**	**91**	**99**	**99**
16.5	Tail pipe N_2O emission factor [g/GJ]	ef_{N2O}	**R [4]**	**0**	**0**	**2.2**	**1.7**	**1.8**	**4.8**	**3.9**
17.5	Efficiency of Euro (?) N_2O measures	h_{N2O}	**R [4]**	**-**	**-**	**0**	**20**	**18**	**-121**	**-80**
18.5	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	**R [4]**							
	1,3 Butadiene			**1.21**	**1.55**	**1.66**	**0.69**	**0.39**	**0.45**	**0.44**
	Benzene			**0.90**	**1.17**	**0.35**	**0.49**	**0.39**	**0.91**	**0.89**
	Formaldehyde			**7.54**	**7.77**	**3.84**	**0.84**	**0.39**	**0.45**	**0.44**
	Acetaldehyde			**3.01**	**3.89**	**1.55**	**1.03**	**0.78**	**0.91**	**0.89**
19.5	Efficiency of Euro (?) VOC measures	h_{VOC}	**R [4]**	**0**	**-14**	**42**	**76**	**85**	**79**	**79**
20.5	Tail pipe SO2 emission factor [g/GJ]	ef_{SO2}	**R [4]**	**5.50**	**5.47**	**1.35**	**0.69**	**0.10**	**0.10**	**0.12**
21.5	Efficiency of Euro (?) SO2 measures	h_{SO2}	**R [4]**	**0**	**1**	**76**	**87**	**98**	**98**	**98**
22.5	Tail pipe NH3 emission factor [g/GJ]	ef_{NH3}	**R [4]**	**0**	**0**	**3.45**	**1.68**	**1.72**	**10.41**	**11.27**
23.5	Efficiency of Euro (?) NH3 measures	h_{NH3}	**R [4]**	**-**	**-**	**0**	**51**	**50**	**-201**	**-226**

Key Results: Diesel LDT Discussion

- Similar technology requirements, fuel economy and emissions constraints to diesel passenger car
  - NOx remains key issue. NOx aftertreatment presents significant control challenges and remains costly
- Analysis assumes manufacturers continue to increase engine performance and limit downsizing
  - Diesel engine specific power substantially increased since 1990 but engine displacements have remained steady
  - Political or legislative actions may result in smaller engines, which could lead to greater challenges to reduce NOx but would reduce CO2 emissions
- Maintenance costs factored to account for increased vehicle usage
- Beyond 2010 it is anticipated that satellite based positioning systems could offer improved compromises, allowing the engine to optimise for emissions in built up areas and fuel economy away from towns and cities

Key Results: Diesel Medium Duty Truck Technology Development

Item		Euro Emissions Legislation / Year of introduction						
		0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced plus: Further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced, further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE but: SCR may replace EGR in some medium duty engine applications	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced, further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE but: Increased use of SCR and other aftertreatment. Further updated FIE, ever more complex control systems. Difficult to estimate true impact.

- Only additional technologies are shown in line item 1 of later graphs

Key Results: Medium Duty Truck Cost and Fuel Economy

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	As Euro 3; further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, but SCR may replace EGR in some medium duty engine applications	Difficult to estimate. Increased use of SCR and other aftertreatment. Further updated FIE, with ever more complex control systems
	Assumptions		Baseline truck engine with no emissions equipment, at €7000						
2	Investment Costs [Euro]	*I*	**0**	**943**	**1778**	**3048**	**5271**	**5657**	**6250**
3	Additional Operating and Maintenance costs [Euro]	*f*	**0**	**274**	**1291**	**1962**	**4054**	**3596**	**3222**
5	Lifetime of control Equipment [years]	*lt*	**10**	**10**	**10**	**10**	**10**	**10**	**10**
9	Change in fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	**100**	**100**	**102**	**105.7**	**102.4**	**101.8**	**100.5**
10	Average fuel consumption 2005-2010 relative to 1990 [fraction]	*fe*	**1**	**1**	**1.02**	**1.057**	**1.024**	**1.018**	**1.005**

- Maintenance on-costs calculated over operating life of 800,000km
- Line 10 fuel economy determined by assigning a factor to each technology and then calculating the penetration of that technology within the market place

Key Results: MDT Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	As Euro 3; further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, but SCR may replace EGR in some medium duty engine applications	Difficult to estimate. Increased use of SCR and other aftertreatment. Further updated FIE, with ever more complex control systems
11.01	Tail pipe CO emissions [g/kWh]		1.4	1.2	0.723	1.067	0.9	0.9	0.8
11.02	Efficiency of Euro (?) CO measures [%]		0	14	48	24	36	36	43
11.03	Tail pipe HC emissions [g/kWh]		2.15	1.1	0.236	0.112	0.1	0.1	0.09
11.04	Efficiency of Euro (?) HC measures [%]		0	49	89	95	95	95	96
11.05	Tail pipe HC + NOx emissions [g/kWh]		13.15	9.00	6.58	4.80	3.25	1.85	1.69
11.06	Efficiency of Euro (?) HC +NOx measures [%]		0	32	50	63	75	86	87
11.07	Tail pipe NOx emissions [g/kWh]		11	7.9	6.340	4.690	3.15	1.75	1.6
11.08	Efficiency of Euro (?) NOx measures [%]		0	28	42	57	71	84	85
11.09	Tail pipe PM emissions [g/kWh]		-	0.4	0.125	0.087	0.015	0.015	0.013
11.10	Efficiency of Euro (?) PM measures [%]		-	0	69	78	96	96	97

- Values quoted in g/kWh as Euro emissions test is completed on dynamometer test bed. It is not practical to estimate vehicle fuel consumption as applications of a particular engine vary

Key Results: MDT Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	As Euro 3; further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, but SCR may replace EGR in some medium duty engine applications	Difficult to estimate. Increased use of SCR and other aftertreatment. Further updated FIE, with ever more complex control systems
11.51	Tail pipe CO emissions [g/GJ]		**157**	**135**	**80**	**113**	**99**	**99**	**89**
11.52	Efficiency of Euro (?) CO measures [%]		**0**	**14**	**49**	**28**	**37**	**37**	**43**
11.53	Tail pipe HC emissions [g/GJ]		**241**	**123**	**26**	**12**	**11**	**11**	**10**
11.54	Efficiency of Euro (?) HC measures [%]		**0**	**49**	**89**	**95**	**95**	**95**	**97**
11.55	Tail pipe HC + NOx emissions [g/GJ]		**1475**	**1010**	**723**	**510**	**356**	**204**	**189**
11.56	Efficiency of Euro (?) HC +NOx measures [%]		**0**	**32**	**51**	**65**	**76**	**86**	**87**
11.57	Tail pipe NOx emissions [g/GJ]		**1234**	**886**	**697**	**498**	**345**	**193**	**179**
11.58	Efficiency of Euro (?) NOx measures [%]		**0**	**28**	**43**	**60**	**72**	**84**	**86**
11.59	Tail pipe PM emissions [g/GJ]		**-**	**111**	**35**	**24**	**4**	**4**	**4**
11.60	Efficiency of Euro (?) PM measures [%]		**-**	**0**	**69**	**78**	**83**	**83**	**85**

- Values in g/GJ Fuel-In based on estimated ESC cycle fuel consumption

Key Results: MDT Unregulated Emissions – g/km

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**	R	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	As Euro 3; further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, but SCR may replace EGR in some medium duty engine applications	Difficult to estimate. Increased use of SCR and other aftertreatment. Further updated FIE, with ever more complex control systems
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	**0.357**	**0.231**	**0.112583333**	**0.08106**	**0.0168875**	**0.00525**	**0.005**
13	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	**0**	**35**	**68**	**77**	**95**	**99**	**99**
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	**0.408**	**0.264**	**0.128666667**	**0.09264**	**0.0193**	**0.006**	**0.005**
15	Efficiency of Euro (?) PM10 measures	h_{PM10}	**0**	**35**	**68**	**77**	**95**	**99**	**99**
16	Tail pipe N_2O emission factor [g/km]	ef_{NOx}	**0**	**0**	**0**	**0**	**0**	**0.01**	**0.012**
17	Efficiency of Euro (?) N_2O measures	h_{NOx}	**-**	**-**	**-**	**-**	**-**	**0**	**-20**
18	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	4						
	1,3 Butadiene		**0.007**	**0.007**	**0.005**	**0.002**	**0.001**	**0.001**	**0.001**
	Benzene		**0.004**	**0.004**	**0.002**	**0.001**	**0.001**	**0.002**	**0.002**
	Formaldehyde		**0.03**	**0.03**	**0.022**	**0.02**	**0.008**	**0.005**	**0.004**
	Acetaldehyde		**0.02**	**0.02**	**0.013**	**0.01**	**0.005**	**0.002**	**0.002**
19	Efficiency of Euro (?) VOC measures	h_{VOC}	**0**	**0**	**31**	**46**	**75**	**84**	**85**
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	**0.001225**	**0.001225**	**0.00035**	**0.00018**	**5.00E-05**	**4.97E-05**	**4.91E-05**
21	Efficiency of Euro (?) SO2 measures	h_{SO2}	**0**	**0**	**71**	**86**	**96**	**96**	**96**
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	**0**	**0**	**0.0113**	**0.011**	**0.011**	**0.02**	**0.024**
23	Efficiency of Euro (?) NH3 measures	h_{NH3}	**-**	**-**	**0**	**3**	**3**	**-77**	**-112**

Key Results: MDT Unregulated Emissions – g/GJ

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Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**	R	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUPs and EUIs in some medium duty engines	All engines are TCA, HP Electronic FIE for control of PM-NOx trade-off. Timing retard for low NOx, some use of EGR and/or EUPs, CR introduced	As Euro 3; further NOx reduction by either using EGR or SCR. Likely strategies are: either EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, but SCR may replace EGR in some medium duty engine applications	Difficult to estimate. Increased use of SCR and other aftertreatment. Further updated FIE, with ever more complex control systems
12.5	Tail pipe PM2.5 emissions factor [g/GJ]	$ef_{PM2.5}$	**47.2**	**30.6**	**14.6**	**10.1**	**2.2**	**0.7**	**0.7**
13.5	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	**0**	**35**	**69**	**79**	**95**	**99**	**99**
14.5	Tail pipe PM10 emission factor [g/GJ]	ef_{PM10}	**54.0**	**34.9**	**16.7**	**11.6**	**2.5**	**0.8**	**0.7**
15.5	Efficiency of Euro (?) PM10 measures	h_{PM10}	**0**	**35**	**69**	**79**	**95**	**99**	**99**
16.5	Tail pipe N_2O emission factor [g/GJ]	ef_{N2O}	**0**	**0**	**0.0**	**0.0**	**0.0**	**1.3**	**1.6**
17.5	Efficiency of Euro (?) N_2O measures	h_{N2O}	**-**	**-**	**-**	**-**	**-**	**0**	**-22**
18.5	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	4						
	1,3 Butadiene		**0.93**	**0.93**	**0.65**	**0.25**	**0.13**	**0.13**	**0.13**
	Benzene		**0.53**	**0.53**	**0.26**	**0.13**	**0.13**	**0.26**	**0.26**
	Formaldehyde		**3.97**	**3.97**	**2.85**	**2.50**	**1.03**	**0.65**	**0.53**
	Acetaldehyde		**2.65**	**2.65**	**1.69**	**1.25**	**0.65**	**0.26**	**0.26**
19.5	Efficiency of Euro (?) VOC measures	h_{VOC}	**0**	**0**	**32**	**49**	**76**	**84**	**85**
20.5	Tail pipe SO2 emission factor [g/GJ]	ef_{SO2}	**0.16**	**0.16**	**0.05**	**0.02**	**0.01**	**0.01**	**0.01**
21.5	Efficiency of Euro (?) SO2 measures	h_{SO2}	**0**	**0**	**72**	**86**	**96**	**96**	**96**
22.5	Tail pipe NH3 emission factor [g/GJ]	ef_{NH3}	**0**	**0**	**1.47**	**1.38**	**1.42**	**2.60**	**3.16**
23.5	Efficiency of Euro (?) NH3 measures	h_{NH3}	**-**	**-**	**0**	**6**	**3**	**-77**	**-116**

Key Results: Medium Duty Truck Discussion

- Fuel economy seen to deteriorate from Euro 0 to Euro 3 as injection timing was retarded to meet Euro 2 and Euro 3 NOx emissions requirements
- Fuel economy likely to be stable or improved at Euro 4 and Euro 5 due to improved combustion and fuel injection systems, use of electronic control and use of EGR and/or SCR for NOx reduction, enabling injection timing to be re-optimised with greater emphasis on fuel economy
- Maintenance costs expected to vary
  - Significant increase at Euro 4 due to the introduction of DPF and EGR systems. Reduction after Euro 4 due to reduction in use of DPF and increase in use of SCR
  - DPF servicing costs estimated at 1 hour labour, completed annually
- Some SCR expected for Euro 4 will require Urea infrastructure
  - **Urea costs not included**, should be calculated from fuel usage (it is outside the scope of this study to estimate fuel consumption)
    - Infrastructure costs of Urea system will be rolled into the urea cost
    - Expected urea cost = €0.5 to €1 per litre, the exact price will be determined in the market
    - Urea requirement = ~ 4 % of fuel consumption

Key Results: Heavy Duty Truck Technology Development

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Item		Euro Emissions Legislation / Year of introduction						
		0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**	Improved combustion system and FIE match	Improved combustion system and FIE match plus: Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	Improved combustion system and FIE match with higher pressure FIE for PM control, timing retard for NOx reduction plus: All engines are TCA, High Pressure Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	Improved combustion system and FIE match with higher pressure FIE for PM control, timing retard for NOx reduction. All engines are TCA, High Pressure Electronic FIE for control of PM, Further timing optimisation for low NOx plus: Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	Improved combustion system and FIE match, timing retard for NOx reduction. All engines are TCA, Higher Pressure Electronic FIE for control of PM, timing optimisation for low NOx. EUI/EUP widespread, CR introduced plus: further NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	Improved combustion system and FIE match, timing retard for NOx reduction. All engines are TCA, Higher Pressure Electronic FIE for control of PM, timing optimisation for low NOx. EUI/EUP widespread, CR introduced, further NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, EGR+updated FIE+Oxi-cat, or SCR+updated FIE. Trend away from EGR towards SCR anticipated	Improved combustion system and FIE match, timing retard for NOx reduction. All engines are TCA, Higher Pressure Electronic FIE for control of PM, timing optimisation for low NOx. EUI/EUP widespread, CR introduced, further NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, EGR+updated FIE+Oxi-cat, or SCR+updated FIE. Plus further increased use of SCR, updated FIE, more complex engine control system

- Only additional technologies are shown in line item 1 of later graphs

Key Results: Heavy Duty Truck Cost and Fuel Economy

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Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
	Assumptions		Baseline truck engine with no emissions equipment, at €14,300						
2	Investment Costs [Euro]	*I*	**0**	**1983**	**3734**	**5121**	**9730**	**10809**	**12250**
3	Additional Operating and Maintenance costs [Euro]	*f*	**0**	**80**	**1332**	**2229**	**3867**	**3885**	**4053**
5	Lifetime of control Equipment [years]	*lt*	**12**	**12**	**12**	**12**	**12**	**12**	**12**
9	Change in fuel consumption caused by implementation of the Euro (?) measures [%]	λ^e	**100**	**100**	**102**	**105.7**	**102.4**	**101.8**	**101.2**
10	Average fuel consumption 2005-2010 relative to 1990 [fraction]	*fe*	**1**	**1**	**1.02**	**1.057**	**1.024**	**1.018**	**1.012**

- Maintenance on-cost calculated over 1,600,000 km
- Fuel economy determined by assigning a factor to each technology and then calculating the penetration of that technology within the market place

Key Results: HDT Emissions

Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
11.01	Tail pipe CO emissions [g/kWh]		1.8	1.25	0.564	0.512	0.5	0.48	0.45
11.02	Efficiency of Euro (?) CO measures [%]		0	31	69	72	72	73	75
11.03	Tail pipe HC emissions [g/kWh]		2.05	1.01	0.260	0.150	0.15	0.14	0.13
11.04	Efficiency of Euro (?) HC measures [%]		0	51	87	93	93	93	94
11.05	Tail pipe HC + NOx emissions [g/kWh]		13.25	8.71	6.56	4.75	3.35	1.89	1.53
11.06	Efficiency of Euro (?) HC +NOx measures [%]		0	34	50	64	75	86	88
11.07	Tail pipe NOx emissions [g/kWh]		11.2	7.7	6.30	4.60	3.2	1.75	1.4
11.08	Efficiency of Euro (?) NOx measures [%]		0	31	44	59	71	84	87.5
11.09	Tail pipe PM emissions [g/kWh]		-	0.6	0.116	0.064	0.015	0.015	0.014
11.10	Efficiency of Euro (?) PM measures [%]		-	0	81	89	98	98	98

- Values quoted in g/kWh as Euro emissions test is completed on dynamometer test bed. It is not practical to estimate vehicle fuel consumption as applications of a particular engine vary

Key Results: HDT Emissions

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Item	Classification / Parameter	Symbol	Euro Emissions Legislation / Year of introduction						
			0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
11.51	Tail pipe CO emissions [g/GJ]		**202**	**140**	**62**	**54**	**55**	**53**	**50**
11.52	Efficiency of Euro (?) CO measures [%]		**0**	**31**	**69**	**73**	**73**	**74**	**75**
11.53	Tail pipe HC emissions [g/GJ]		**230**	**113**	**29**	**16**	**16**	**15**	**14**
11.54	Efficiency of Euro (?) HC measures [%]		**0**	**51**	**88**	**93**	**93**	**93**	**97**
11.55	Tail pipe HC + NOx emissions [g/GJ]		**1486**	**977**	**721**	**504**	**367**	**208**	**170**
11.56	Efficiency of Euro (?) HC +NOx measures [%]		**0**	**34**	**51**	**66**	**75**	**86**	**89**
11.57	Tail pipe NOx emissions [g/GJ]		**1256**	**864**	**693**	**488**	**351**	**193**	**155**
11.58	Efficiency of Euro (?) NOx measures [%]		**0**	**31**	**45**	**61**	**72**	**85**	**88**
11.59	Tail pipe PM emissions [g/GJ]		**-**	**167**	**32**	**18**	**4**	**4**	**4**
11.60	Efficiency of Euro (?) PM measures [%]		**-**	**0**	**81**	**89**	**77**	**77**	**78**

- Values in g/GJ Fuel-In based on estimated ESC cycle fuel consumption

Key Results: HDT Unregulated Emissions – g/km

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Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		**R** [1]	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
12	Tail pipe PM2.5 emissions factor [g/km]	$ef_{PM2.5}$	**R** [4]	**0.546**	**0.35525**	**0.1365**	**0.09828**	**0.020475**	**0.00525**	**0.00525**
13	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	**R** [4]	**0**	**35**	**75**	**82**	**96**	**99**	**99**
14	Tail pipe PM10 emission factor [g/km]	ef_{PM10}	**R** [4]	**0.624**	**0.406**	**0.156**	**0.11232**	**0.0234**	**0.006**	**0.006**
15	Efficiency of Euro (?) PM10 measures	h_{PM10}	**R** [4]	**0**	**35**	**75**	**82**	**96**	**99**	**99**
16	Tail pipe N_2O emission factor [g/km]	ef_{N2O}	**R** [4]	**0**	**0**	**0**	**0**	**0**	**0.018**	**0.022**
17	Efficiency of Euro (?) N_2O measures	h_{N2O}	**R** [4]	**-**	**-**	**-**	**-**	**-**	**0**	**-20**
18	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	**R** [4]							
	1,3 Butadiene			**0.007**	**0.006**	**0.006**	**0.003**	**0.0015**	**0.0014**	**0.0014**
	Benzene			**0.004**	**0.004**	**0.002**	**0.001**	**0.0015**	**0.0028**	**0.0029**
	Formaldehyde			**0.029**	**0.028**	**0.024**	**0.027**	**0.012**	**0.007**	**0.0058**
	Acetaldehyde			**0.019**	**0.018**	**0.014**	**0.013**	**0.0075**	**0.0028**	**0.0029**
19	Efficiency of Euro (?) VOC measures	h_{VOC}	**R** [4]	**0**	**4**	**20**	**24**	**61**	**76**	**78**
20	Tail pipe SO2 emission factor [g/km]	ef_{SO2}	**R** [4]	**0.0022**	**0.0022**	**0.0006**	**0.0003**	**9.15E-05**	**9.09E-05**	**8.98E-05**
21	Efficiency of Euro (?) SO2 measures	h_{SO2}	**R** [4]	**0**	**0**	**71**	**86**	**96**	**96**	**96**
22	Tail pipe NH3 emission factor [g/km]	ef_{NH3}	**R** [4]	**0**	**0**	**0.021**	**0.020**	**0.020**	**0.037**	**0.044**
23	Efficiency of Euro (?) NH3 measures	h_{NH3}	**R** [4]	**-**	**-**	**0**	**3**	**3**	**-77**	**-112**

Key Results: HDT Unregulated Emissions – g/GJ

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Item	Classification / Parameter	Symbol		Euro Emissions Legislation / Year of introduction						
				0 / 1990	1 / 1992	2 / 1996	3 / 2000	4 / 2005	5 / 2010	6 / 2015
1	**Technology Requirement**		R [1]	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
12.5	Tail pipe PM2.5 emissions factor [g/GJ]	$ef_{PM2.5}$	R [4]	**39.5**	**25.7**	**9.7**	**6.7**	**1.4**	**0.4**	**0.4**
13.5	Efficiency of Euro (?) PM2.5 measures [%]	$h_{PM2.5}$	R [4]	**0**	**35**	**75**	**83**	**96**	**99**	**99**
14.5	Tail pipe PM10 emission factor [g/GJ]	ef_{PM10}	R [4]	**45.1**	**29.4**	**11.1**	**7.7**	**1.7**	**0.4**	**0.4**
15.5	Efficiency of Euro (?) PM10 measures	h_{PM10}	R [4]	**0**	**35**	**75**	**83**	**96**	**99**	**99**
16.5	Tail pipe N_2O emission factor [g/GJ]	ef_{N2O}	R [4]	**0**	**0**	**0.0**	**0.0**	**0.0**	**1.3**	**1.6**
17.5	Efficiency of Euro (?) N_2O measures	h_{N2O}	R [4]	**-**	**-**	**-**	**-**	**-**	**0**	**-21**
18.5	Tail pipe VOC emission factor [g/GJ]	ef_{VOC}	R [4]							
	1,3 Butadiene			**0.48**	**0.46**	**0.39**	**0.18**	**0.11**	**0.10**	**0.10**
	Benzene			**0.28**	**0.27**	**0.16**	**0.09**	**0.11**	**0.20**	**0.21**
	Formaldehyde			**2.07**	**1.99**	**1.72**	**1.84**	**0.85**	**0.50**	**0.41**
	Acetaldehyde			**1.38**	**1.33**	**1.02**	**0.92**	**0.53**	**0.20**	**0.21**
19.5	Efficiency of Euro (?) VOC measures	h_{VOC}	R [4]	**0**	**4**	**22**	**28**	**62**	**76**	**78**
20.5	Tail pipe SO2 emission factor [g/GJ]	ef_{SO2}	R [4]	**0.16**	**0.16**	**0.05**	**0.02**	**0.01**	**0.01**	**0.01**
21.5	Efficiency of Euro (?) SO2 measures	h_{SO2}	R [4]	**0**	**0**	**72**	**86**	**96**	**96**	**96**
22.5	Tail pipe NH3 emission factor [g/GJ]	ef_{NH3}	R [4]	**0**	**0**	**1.47**	**1.38**	**1.42**	**2.60**	**3.14**
23.5	Efficiency of Euro (?) NH3 measures	h_{NH3}	R [4]	**-**	**-**	**0**	**6**	**3**	**-77**	**-114**

Key Results: Heavy Duty Truck Discussion

- Significant portion of modern diesel engine cost is related to emissions reduction (now ~30% and expected to increase)
- Maintenance and running costs expected to increase steadily
  - Increased use of aftertreatment
  - Annual DPF service included as with MDT
  - Similar equipment life expectancies to MDT, but parts generally more expensive
  - Urea requirement and cost as for MDT engines
- Similar trend in fuel economy to medium duty engines is for similar reasons
- Diesel fuel density and energy assumed to be the same as for passenger car when calculating unregulated emission values in g/GJ

Contents

Estimated Maintenance Cost

- OEM data on equipment failure rates is not published. Estimated failure rates have been based on Ricardo experience from the following:
  - Individual engineer's experience
  - Failure rates seen in testing
  - Known deterioration factors
- In all cases, only emissions related equipment has been included
- It is assumed that the emissions system will be allowed to degrade over the lifetime of the vehicle, therefore
  - Equipment would only be replaced when there is a noticeable problem
    - Loss of power, fuel economy or other factor affecting driveability
    - OBD light on vehicle dashboard
    - Failure to meet a government emissions test
  - Equipment will be near the end of its useful life when the vehicle is scrapped
  - Scrapping due to a failure to meet emissions compliance has not been included in these costs, as the vehicle must be beyond economical repair for this to occur and therefore is close to the end of its life in any case

Estimated Maintenance Cost

- Total failures are estimated over the life expectancy of an average vehicle (i.e. how far an average vehicle in each sector may be expected to drive during its entire life)
  - Gasoline car = 150,000 km
  - Gasoline LDT = 175,000 km
  - Diesel car = 200,000 km
  - Diesel LDT = 240,000 km
  - Diesel MDT = 800,000 km
  - Diesel HDT = 1,600,000 km
- The estimated failure rates are combined with the cost of each component to the OEM, multiplied by factors to include distribution, fitting costs and profit
- This figure is then contrasted with the penetration of that technology to determine the cost to the average vehicle for each level of emissions legislation

Estimated Maintenance Cost

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- Example of 3-way catalytic converter:
  - Mainly introduced in 1991
  - OEM pays around €80 to €120 today depending on catalyst loading, precious metal cost, manufacturer and volume
  - Early catalysts had degradation factors of ~50% over 120,000km
  - Current catalysts have degradation factors of ~6% over the same distance, and ~20% over 200,000km
    - Improvements to transient fuelling have reduced thermal damage to precious metals, and reduced incidences of catalyst failure
  - But when would a catalyst be replaced?
    - Up to 2000 the catalyst was only tested during required inspection (may not detect a problem until the catalyst is extremely degraded)
    - OBD sensors to rear of catalyst improve detection of catalyst problems
    - Hence only a proportion of vehicles will require a replacement catalyst at 150,000km

Estimated Maintenance Cost

- Example of 3-way catalytic converter continued:
  - Estimate that 4% of catalysts had to be replaced in 1992, and 8% in 2000
  - BUT cost to end user is far greater than the OEM pays its supplier
    - Cost to end user can range between 3 and 9 times purchase price
    - Assume piece cost to end user is 5 times purchase price including fitting
  - Cost of part is therefore around €100 x 5 = €500 (plus tax)
  - Hence, assuming cost does not vary
    - Cost per vehicle in 1992 = €500 x 4/100 = €20
    - Cost per vehicle in 2000 = €500 x 8/100 = €40

- Note: Catalyst price for this survey actually taken as €90 plus amortised tooling costs

Example of Estimated Failures: Gasoline Car

Euro Emissions Standard	0	1	2	3	4	5	6
Year of Introduction:	< 1992 (1990)	1992	1996	2000	2005	2010	2015
Emissions Technology Requirement (Majority of Vehicles)	Carburettor / Single Point Injection / Distributor Ignition / Limited use of electronic control	3-way Catalyst / Lambda sensor / Electronic Injection / Electronic Ignition / Basic evaporative emissions equipment	Better hardware design / Higher cat loading / Some use of EGR / Multi-point injection	Post cat O2 / Revised controller and software / Higher catalyst loading / Evaporative emissions equipment / Reduced base engine friction	Starter (pup) cat / revised high speed fuelling strategy (keep cat cool) / Increased use of EGR or variable cam phasing	Variable cam phasing / Increased use of lean burn direct Injection	General refinement / Increased use of direct injection / boosted downsized engines / wider introduction of hybrid technologies
Three Way Catalyst	0.050	0.040	0.030	0.080	0.060	0.045	0.030
Lambda Sensor - Unheated	0.043	0.043	0.043	0.034	0.034	0.026	0.026
Electronic Ignition System	0.129	0.095	0.069	0.069	0.069	0.069	0.069
Distributorless electronic Ignition System	0.043	0.034	0.034	0.034	0.026	0.026	0.026
Control System	0.350	0.280	0.230	0.200	0.170	0.150	0.120
EGR valve / plumbing	0.172	0.129	0.129	0.103	0.086	0.069	0.060
Post catalyst oxygen sensors	0.086	0.086	0.086	0.086	0.086	0.086	0.086
Evaporative emissions equipment	0.026	0.026	0.026	0.026	0.017	0.017	0.017
Starter / Light off catalyst	0.000	0.000	0.000	0.000	0.002	0.002	0.003
Secondary air system	0.001	0.001	0.001	0.017	0.017	0.017	0.017
Turbo and Ducting	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Charge Cooler	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Variable cam phasing	0.086	0.043	0.022	0.010	0.009	0.060	0.004
Direct Injection	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Lean Nox trap	0.500	0.400	0.350	0.320	0.300	0.270	0.250
Wide range lambda sensors	0.043	0.034	0.026	0.017	0.009	0.009	0.009
Single point injection unit	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Multi point injection equipment	0.069	0.026	0.017	0.017	0.009	0.009	0.009
Mild Hybrid	0.430	0.344	0.258	0.172	0.150	0.125	0.100

- Failure rates shows failures per vehicle over a life time of 150,000km (i.e. proportion)
- Sheets like this were generated for each sector thus allowing the maintenance cost to be estimated

Example of Estimated Failures – Heavy Duty Truck

Year of Introduction	1987	1992	1996	2000	2005	2010	2015
European Standards [g/kW.h]	Euro 0 = R49	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
Emissions Technology Content (Majority of Vehicles)	Improved combustion system and FIE match	Higher pressure FIE for PM control, timing retard for NOx reduction, move to TC/TCA	All engines are TCA, HP Electronic FIE for control of PM, Further timing optimisation for low NOx, EUI/EUP for Premium truck	All engines TCA, HP FIE, electronic control. Timing retard for low NOx, some use of EGR, EUI/EUP widespread, CR introduced	As Euro 3, with NOx reduction by using EGR or SCR system. Strategies: EGR+DPF, or EGR+updated FIE+Oxi-cat, or SCR+updated FIE	As Euro 4, buta trend away from EGR towards SCR anticipated	Expect further increased use of SCR, updated FIE, more complex engine control system
TC	3	3	3	3	3	3	3
TCA	3	3	3	3	3.2	3.2	3.2
Energy Recovery Systems							
Turbocompound	2	2	2	2	2	2	2
FUEL INJECTION EQUIPMENT							
Low Press (< 1000 bar) Mechanical FIE	0.2	0.2	0.2	0.2	0.2	0.2	0.2
High Pressure Mechanical e.g. RP43, RP25	0.2	0.2	0.2	0.2	0.2	0.2	0.2
HP Rotary FIE	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Electronic Rotary FIE	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Common rail FIE	0.5	0.5	0.5	0.5	0.5	0.5	0.5
EUI/EUP FIE	1	1	1	1	1	1	1
Others (HPI)	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Advanced EUI/EUP (such as E3)	1	1	1	1	1	1	1
Nozzle Types							
Minisac Nozzles	1	1	1	1	1	1	1
VCO Nozzles	1	1	1	1	1	1	1
Others (HPI)	1	1	1	1	1	1	1
Extrude-honed Nozzles	0	0	0	0	0	0	0
NOx Reduction Technology							
EGR	0.75	0.75	0.75	0.75	0.75	0.75	0.75
EGR cooler	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SCR inj system	0.75	0.75	0.75	0.75	0.75	0.75	0.75
SCR catalyst	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Lean NOx trap	1	1	1	1	1	1	1
Aftertreatment							
Catalyst - Oxidation	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Diesel Particulate Filter	0.5	0.5	0.5	0.5	0.5	0.5	0.5

- Information shown in incidents per vehicle equipped with each technology over 800,000km life span (i.e. some components expected to be replaced more than once)

Estimated Maintenance Cost

- Major emissions related repairs include
  - Gasoline:
    - Control system (although not always in relation to emissions systems)
    - Lambda sensors (becoming more reliable with improved fuelling control)
    - Expect to see increased operating costs due to increased use of direct injection (LNT and fuel injection equipment costs)
  - Light Duty Diesel
    - Control system
    - Fuel pump
    - Turbocharger
  - Medium and Heavy Duty Diesel
    - Control System
    - Fuel injection system
    - After-treatment system, e.g. DPF servicing

Contents

Emissions - Regulated

- Most regulated emissions data from Government sources
  - Sample size of as many as possible
  - Gasoline car engine sizes from 1200cc to 2000cc
    - Average around 1700cc
  - Diesel car engine sizes from 1500 to 2000cc
    - Average around 1750cc
  - Truck engine emissions based upon calibrated safety factors, e.g. engineers may calibrate NOx up to 75% of the limit
- Limiting factor on diesel engines is normally NOx or PM, hence CO and HC's are normally further back from the legislated limit

Emissions - Regulated

- Values quoted are for “de-greened” type approval vehicles and do not account for deterioration of emissions related equipment
  - Deterioration varies over time and duty cycle
    - Early 3 way catalysts thought to degrade by up to 50% over 125,000 km but even so could still pass UK government emissions inspection
    - Modern 3-way catalyst expected to degrade not more than 20% over lifetime of vehicle and substantially outlast legally required lifetime
    - Unknown how long LNT technology will last. This equipment is extremely sensitive to heat, such as is seen during desulphation. N.B. The technology is still under development
- HC and CO values expected to rise with the introduction of LNT technology
  - LNT requires a rich spike to react NOx, resulting in HC and CO increase
  - CO increase should be small but will depend on quality of calibration
  - 3-way catalyst needs to run at or very near stoichiometric air/fuel ratio to operate at maximum efficiency so would be unable to react all HC or CO
- PM levels expected to rise in gasoline engines with as market penetration of direct injection increases

Contents

Emissions - Unregulated

- Unregulated emissions data from numerous sources including Ricardo vehicle tests
- Most damaging VOC's split out to show proportions, total HC limit is regulated and hence shown alongside other regulated emissions
  - No account taken of reactions taking place in the atmosphere after the emissions leave the tail pipe
- Sulphur emissions directly proportional to sulphur level in fuel
  - EC document 2001/0107 proposes to reduce sulphur content to “zero” by 2011 - this has not been taken into account
    - Even then, sulphur in lube oil will still lead to some SO_2 emissions
- Potential for N_2O and NH_3 emissions to rise as a result of new technologies
  - Both diesel and gasoline engines will use technologies such as LNT or SCR to meet future emissions and fuel economy demands

Contents

Conclusions

- Data has been gathered for different vehicle categories as requested by CITEPA
- In-house and external data sources have been used
- For gasoline engines the technology focus is on performance and economy
- For diesel engines the technology focus is on emissions
- Evidence of fuel economy improvement in cars since 1996, expectation that European manufacturers will achieve their fleet target of 140g/km by 2008

Conclusions

- Incremental cost of emissions compliance has been inconsistent, but is expected to increase due to the additional hardware which will be required to meet Euro 5 and, if applicable, Euro 6
- Cost of servicing emissions equipment is and is likely to remain a significant part of vehicle maintenance costs
- Emissions have significantly reduced since the introduction of legislation
- Some of the measures have resulted in increases in undesirable unregulated emissions

Study Sources

- External Sources:
  - New Car Fuel Consumption: British Department of Transport 1990, 1994, 1997, also information from VCA website (www.vca.gov.uk)
  - Schadstoff-Typpruefwerte: German "KBA", Feb 1991, also information from KBA website (www.kba.de)
  - Emissions Standards Passenger Cars Worldwide: Delphi, April 2002
  - ACEA
  - European Gasoline Survey: Associated Octel (from various years)
  - Tracking Emissions from UK Vehicle Exhausts: The AA/NETCEN; June 1997
  - The Use of Constant Volume Sampler and Dilution Tunnel to Compare the Total Particulates from a Range of Automotive Engines: Collins, Cuthbertson, Gawen, Wheeler; SAE 750904; October 1975
  - Coming Clean: Crosse, Autocar and Motor; 18 April 1990
  - Internal Combustion Engine Fundamentals: Heywood; McGraw Hill

Study Sources

- Internal Sources:
  - P.S.R database accessible through Ricardo
  - Ricardo EMLEG database
  - Other confidential sources

“Support for Updating the RAINS Model Concerning Road Transport” Final Report

Supplemental Information

Background Information:
Vehicle Emissions Drive Cycles

European Emissions Requirements: Gasoline Car

- Euro 5 emissions requirements to be defined. Quoted figures are latest estimate

Euro Emissions Standard	0	1	2	3	4	5
Year of Introduction:	< 1992 (1990)	1992	1996	2000	2005	2008
Regulated Mass emissions [g/km]:						
CO Requirement	11.1	2.72	2.2	2.3	1	1
HC Requirement	N/A	N/A	N/A	0.2	0.1	0.1
HC + NOx Requirement	3.7	0.97	0.5	0.35	0.18	0.18
NOx Requirement	1.5	N/A	N/A	0.15	0.08	0.08
PM Requirement	N/A	0.14	N/A	N/A	N/A	0.025

European Emissions Requirements: Gasoline Car

- FR means First Registrations
- Blanks are where no limit was defined (initially HC and NOx were rolled in together)

Euro Emissions Standard	0	1	2	3	4
Year of Introduction:	< 1992 (1990)	1992	1996	2000	2005
Regulated Mass emissions [g/km] (LDT1):		FR 1994	FR 1997	FR 2001	FR 2006
CO Requirement	11.1	2.72	2.2	2.3	1
HC Requirement				0.2	0.1
HC + NOx Requirement	3.7	0.97	0.5	0.35	0.18
NOx Requirement	1.5			0.15	0.08
PM Requirement	N/A	0.14			
Regulated Mass emissions [g/km] (LDT2):					
CO Requirement	11.1	5.17	4	4.17	1.81
HC Requirement				0.25	0.13
HC + NOx Requirement	3.7	1.4	0.6	0.43	0.23
NOx Requirement	1.5			0.18	0.1
PM Requirement	N/A	0.19			
Regulated Mass emissions [g/km] (LDT3):					
CO Requirement	11.1	6.9	5	5.22	2.27
HC Requirement				0.29	0.16
HC + NOx Requirement	3.7	1.7	0.7	0.5	0.27
NOx Requirement	1.5			0.21	0.11
PM Requirement	N/A	0.25			

European Emissions Requirements: Diesel Car and LDT

Euro Emissions Standard	0 (ECE R15/04)	1	2	3	4	5 (draft)
Year of Introduction:	< 1992	1992	1996	2000	2005	2008 / 2010
Mass Emissions Limits [g/km]						
Passenger Cars (GVW<2500kg)						
CO	11.1	2.72	1	0.64	0.5	1
HC	-	-	-	-	-	0.1
HC + NOx	3.7	0.97 (IDI) / 1.36 (DI)	0.7 (IDI) / 0.9 (DI)	0.56	0.3	-
NOx	1.5	-	-	0.5	0.25	0.08
PM	N/A	0.14 (IDI) / 0.196 (DI)	0.08 (IDI) / 0.1 (DI)	0.05	0.025	0.0025
Light Duty Trucks (LDT1 category: rw<1305kg*)						
CO		2.72	1	0.64	0.5	1
HC		-	-	-	-	0.1
HC + NOx		0.97 (IDI) / 1.36 (DI)	0.7 (IDI) / 0.9 (DI)	0.56	0.3	-
NOx		-	-	0.5	0.25	0.08
PM		0.14 (IDI) / 0.2 (DI)	0.08 (IDI) / 0.1 (DI)	0.05	0.025	0.0025
Light Duty Trucks (LDT2 category: 1305kg*<rw<1760kg*)						
CO		5.17	1.25	0.8	0.63	1
HC		-	-	-	-	0.1
HC + NOx		1.4 (IDI) / 1.96 (DI)	1.0 (IDI) / 1.3 (DI)	0.72	0.39	-
NOx		-	-	0.65	0.33	0.08
PM		0.19 (IDI) / 0.27 (DI)	0.12 (IDI) / 0.14 (DI)	0.07	0.04	0.0025
Light Duty Trucks (LDT3 category: 1760kg*>rw)						
CO		6.9	1.5	0.95	0.74	1.25
HC		-	-	-	-	0.125
HC + NOx		1.7 (IDI) / 2.38 (DI)	1.2 (IDI) / 1.6 (DI)	0.86	0.46	-
NOx		-	-	0.78	0.39	0.1
PM		0.25 (IDI) / 0.35 (DI)	0.17 (IDI) / 0.20 (DI)	0.1	0.06	0.032

European Emissions Requirements: Medium and Heavy Duty Truck

- Medium Duty:

Year of Introduction	1987	1992	1996	2000	2005	2008
European Standards [g/kW.h]	Euro 0 = R49	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5
NOx	14.4	8	7	5	3.5	2
HC	2.4	1.1	1.1	ESC/ETC 0.7/0.8	0.5/0.6	0.5/0.6
CO	11.2	3.5	4	2.1/5.45	2.1/5.45	2.1/5.45
PM	Not regulated	0.36=>85 kW, 0.63=<85 kW	0.15	0.1/0.16	0.02/0.03	0.02/0.03

- Heavy Duty:

Year of Introduction	1987	1992	1996	2000	2005	2008
European Standards [g/kW.h]	Euro 0 = R49	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5
NOx	14.4	8	7	5	3.5	2
HC	2.4	1.1	1.1	ESC/ETC 0.7/0.8	0.5/0.6	0.5/0.6
CO	11.2	3.5	4	2.1/5.45	2.1/5.45	2.1/5.45
PM	Not regulated	0.36=>85 kW, 0.63=<85 kW	0.15	0.1/0.16	0.02/0.03	0.02/0.03

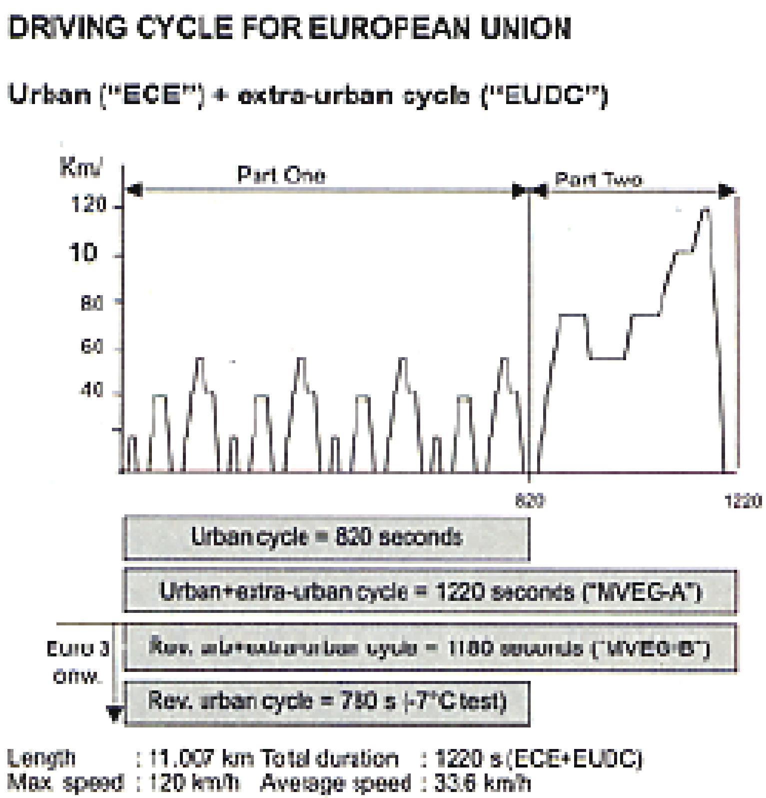
- Note: Heavy Duty engines are tested using a test bed emissions cycle. Results are quoted in g/kWh since a single engine/chassis combination may be used for a range of applications

Emissions Drive Cycles

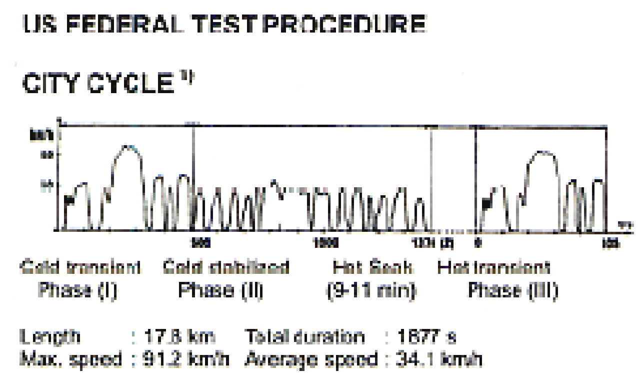
RICARDO

- Emissions Drive Cycles are used to prove a vehicle meets emissions standards. Emissions are measured as the vehicle drives the cycle on a rolling road
- Cycles designed to reflect typical driving habits for that particular region

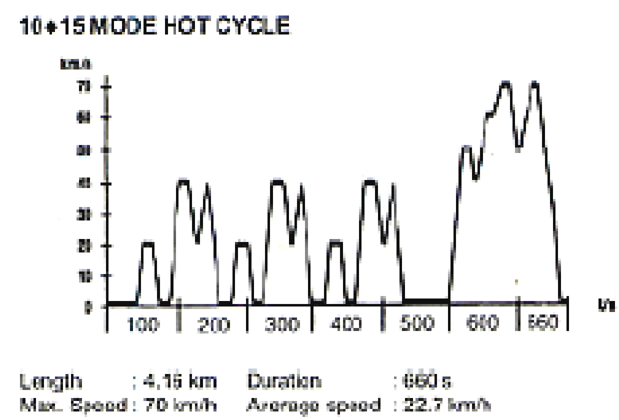
Europe



US Federal



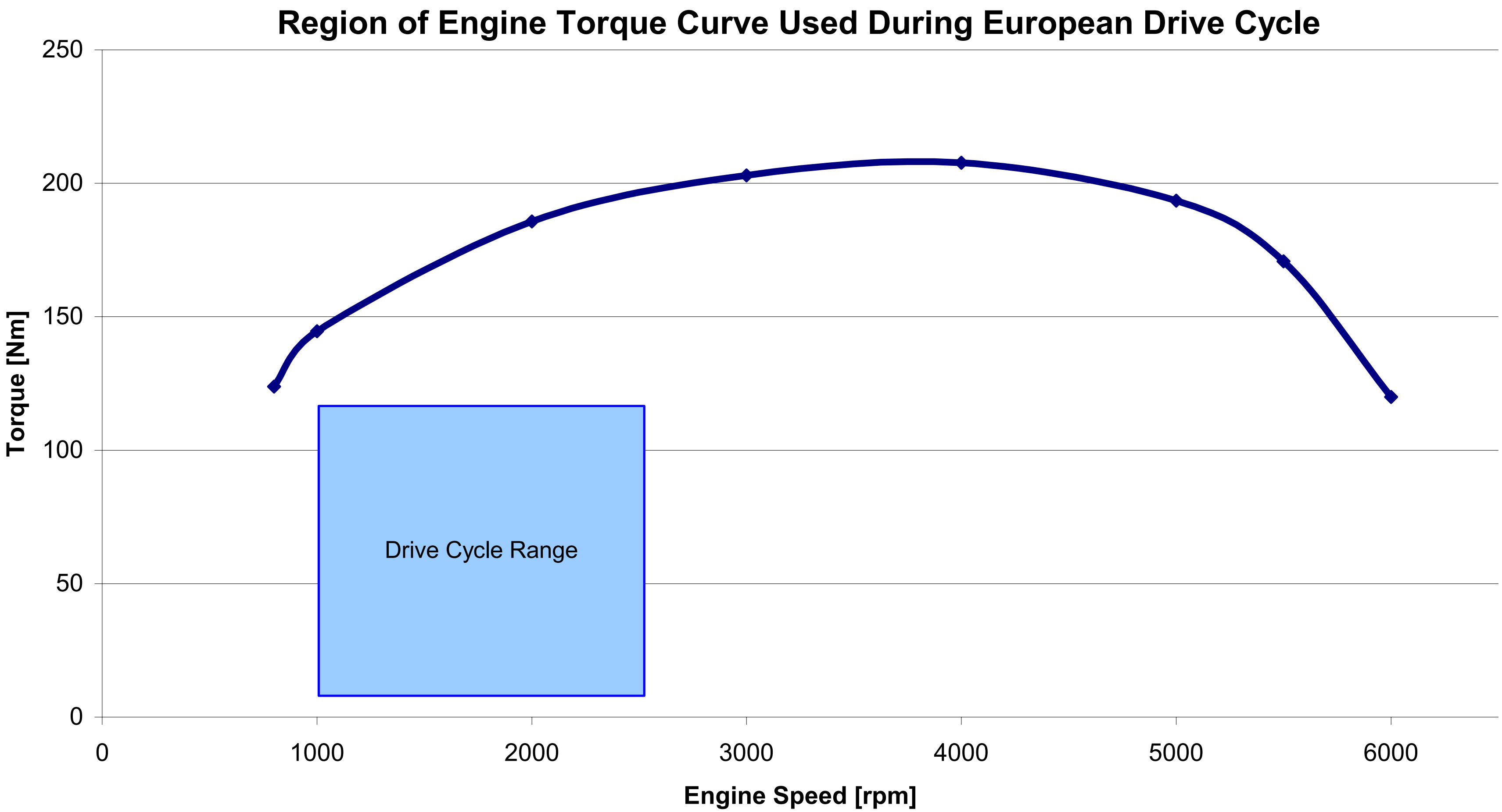
Japan



Extracted from "Emissions Standards Passenger Cars Worldwide"; Delphi

Emissions Cycle: Area Under the Torque Curve

- Drive cycle uses a minimum of engine speed or load, whilst staying within the limits of required vehicle acceleration and speed. The blue square denotes a typical drive cycle region.



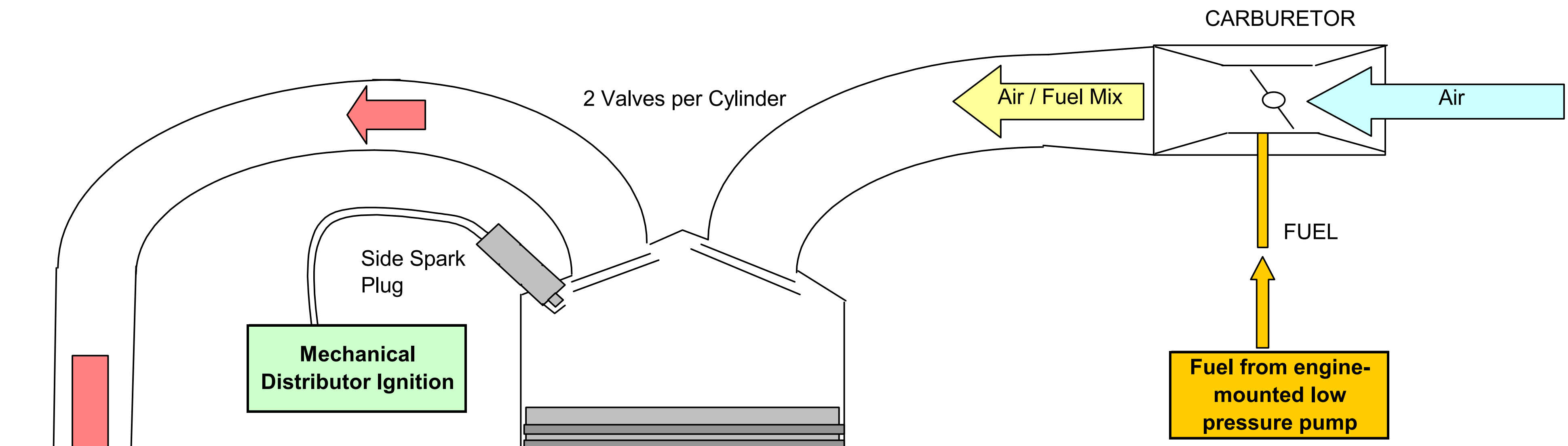
Background Information: Gasoline Engine Technology

Evolution of Gasoline Engines

- Development has been more a matter of continuing development rather than sudden changes
  - Direct gasoline injection has been around since 1940’s
  - After treatment technologies, coupled with the availability of cheaper, electronic, control have been the enabler for improved engine emissions
  - High powered computational capability has aided the development community to increase the pace of development
    - Increased use of analysis has provided the ability to design in 3-D and provide guidance to engineers as to the likely performance of a design before a part has ever been made
    - Improved testing technology has increased the rate of development and the levels of refinement which can be achieved in all areas
    - Ever more powerful engine management hardware and software

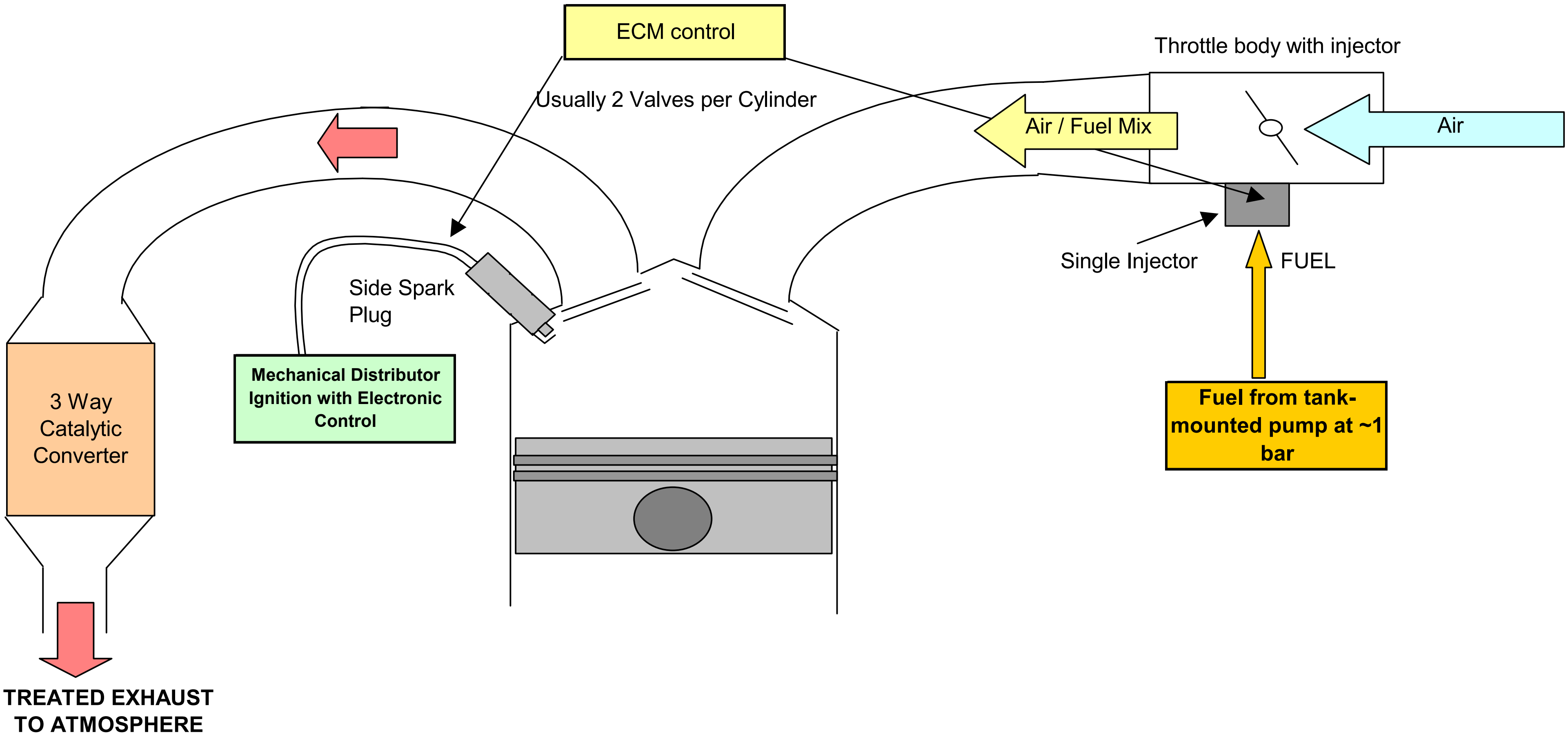
Evolution of Gasoline Engine Technology

1990: Schematic of basic, carburetted engine



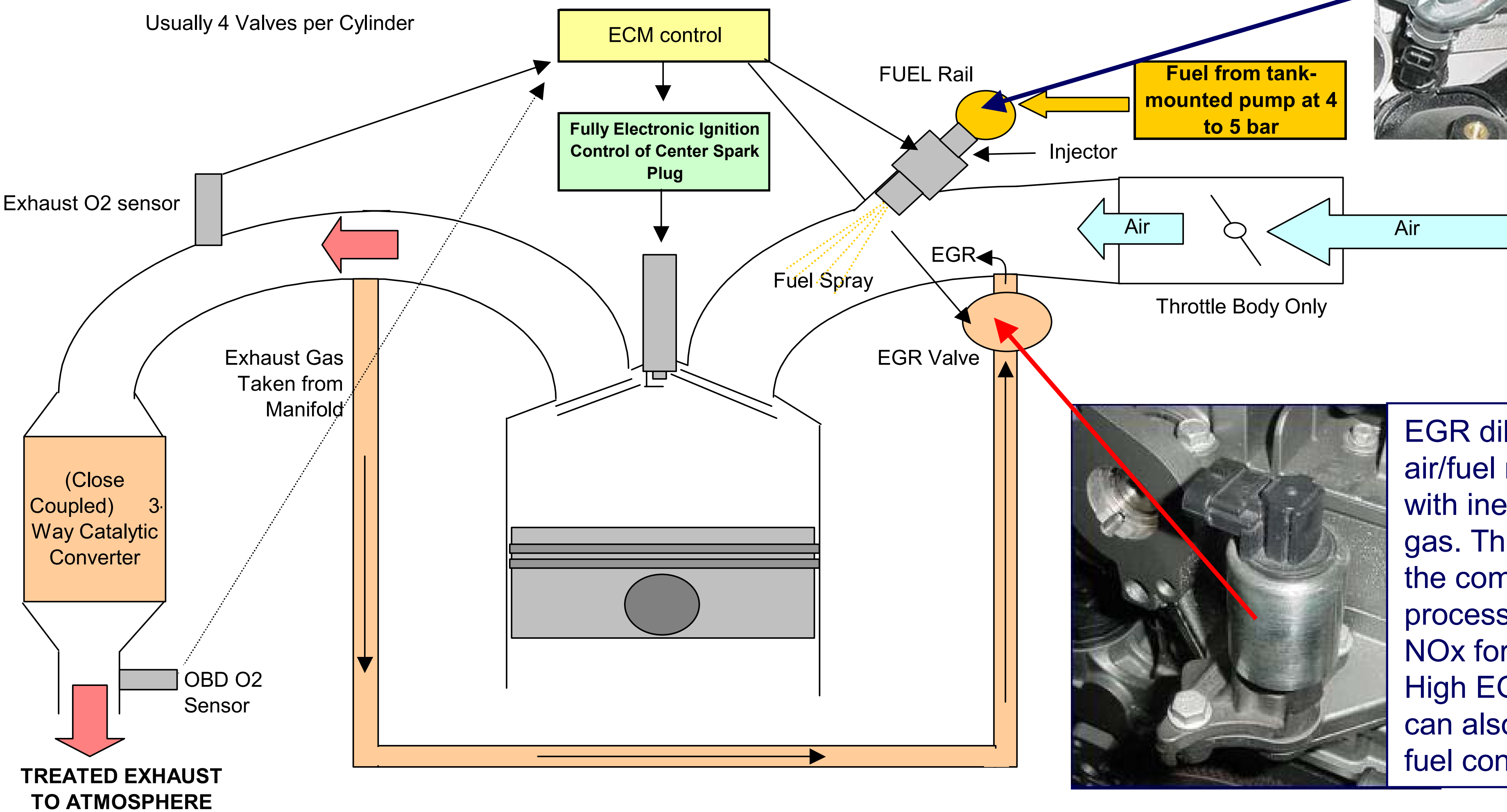
Evolution of Gasoline Engine Technology

1992: Simple single-point injection system (shown), premium cars using multi-point port fuel injection



Evolution of Gasoline Engine Technology

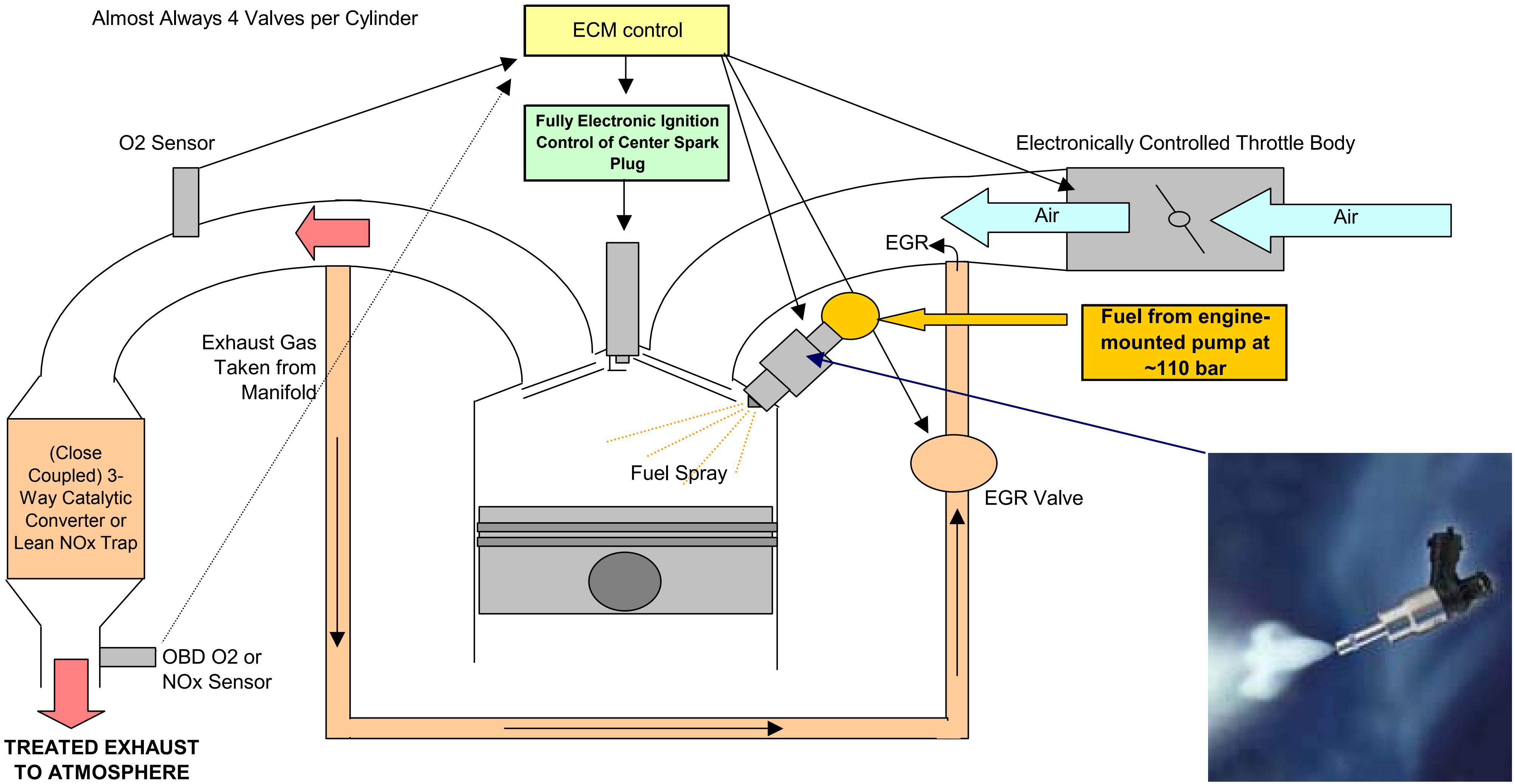
1996: Schematic of port fuel injected engine with EGR



EGR dilutes the air/fuel mixture with inert exhaust gas. This slows the combustion process, reducing NOx formation. High EGR rates can also reduce fuel consumption.

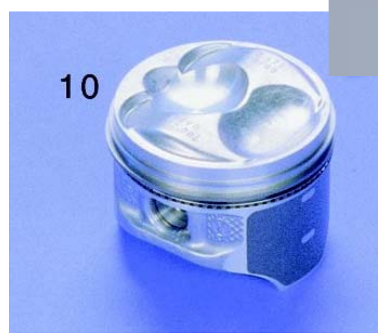
Evolution of Gasoline Engine Technology

2003: Schematic of advanced, direct injected gasoline engine



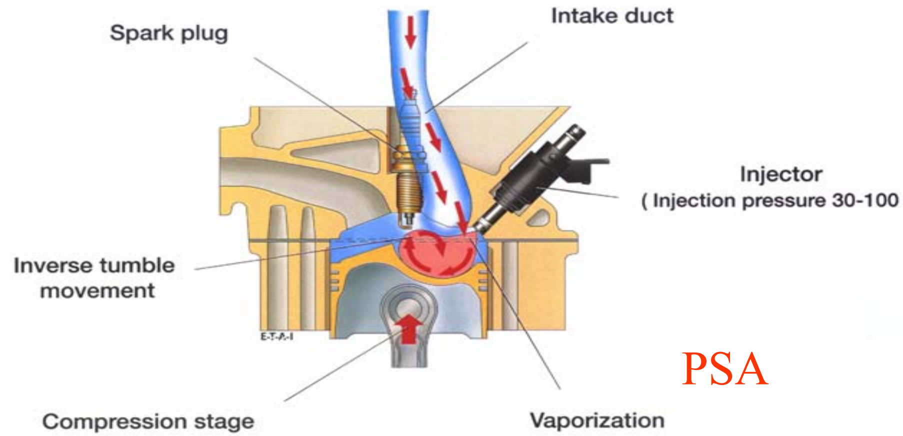
Fundamentals of GDI Combustion

- Hardware changes from port injected engine:
  - Revised piston design
  - Revised cylinder head design (porting)
  - Higher compression ratio
  - SIDI Injectors
  - High pressure fuel pump (~1450 psi), typically camshaft driven
  - Revised EGR system or camshaft phasing
  - Lean NOx catalyst and NOx sensor for lean engines
  - Variable geometry intake for some lean engines
  - Revised control system and calibration
  - Still need a spark plug!

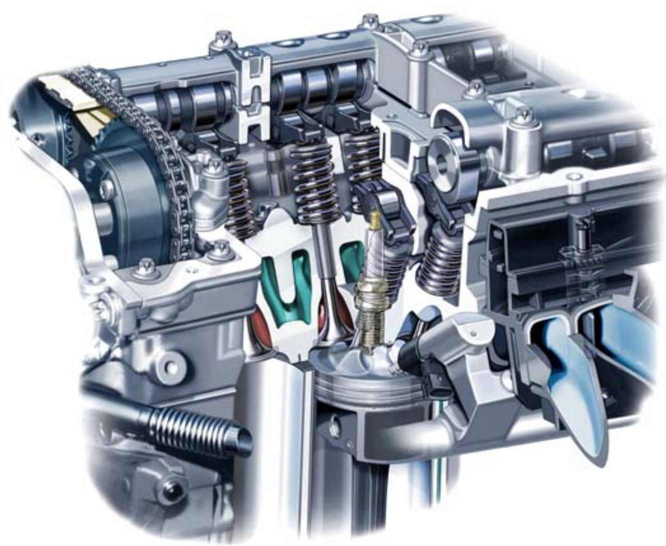


Current production SIDI combustion systems

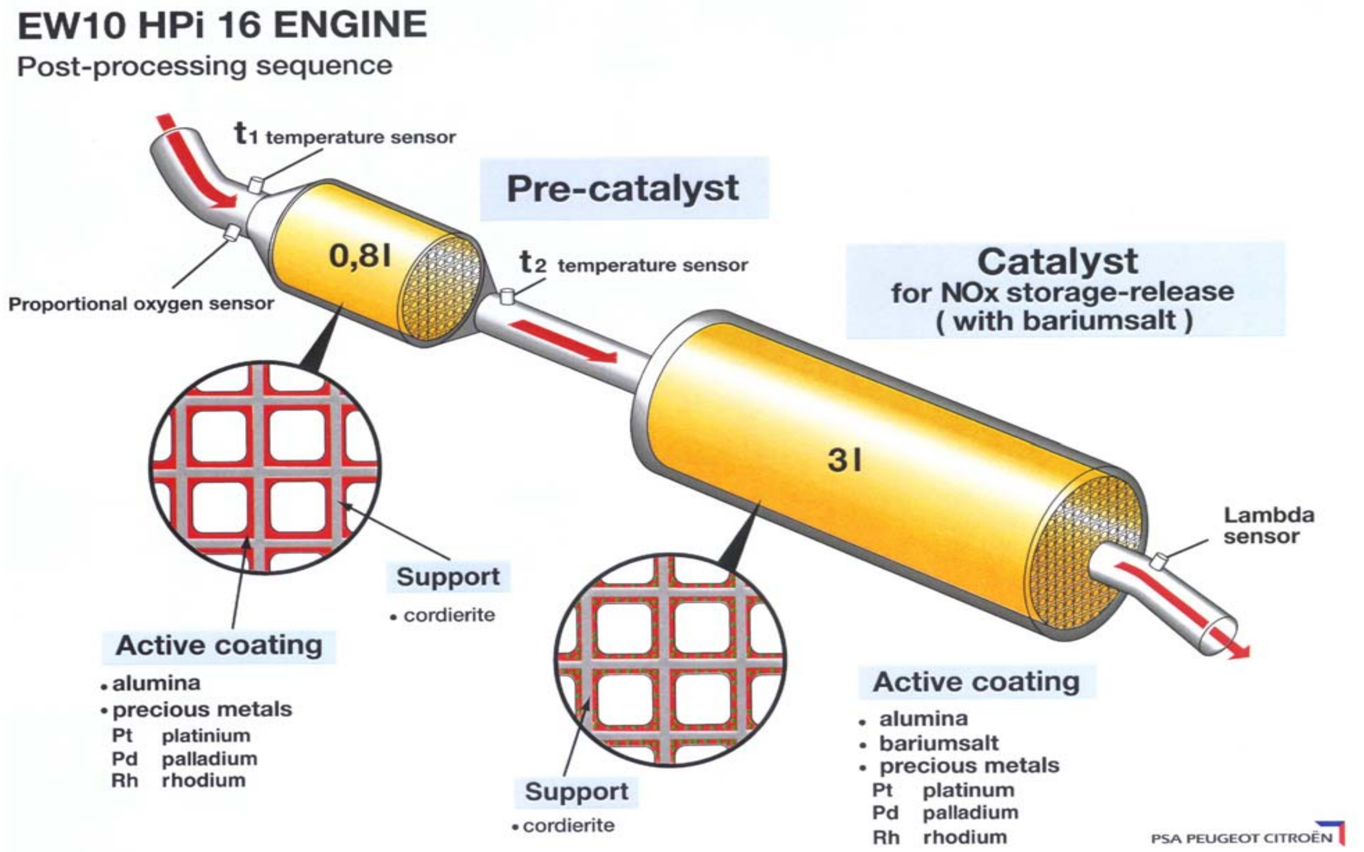
- Combustion system layouts
  - Reverse tumble / wall guided
    - Top entry ports
    - Mitsubishi GDI
    - PSA HPi
  - Swirling / wall guided
    - Side entry ports
    - Toyota
    - Nissan
    - Mercedes CGI
  - Forward tumble / air guided
    - Side entry ports
    - VW/Audi FSI
    - BMW (homogeneous)
    - Alfa JTS (homogeneous with strat idle)
  - Central injector
    - Side entry ports
    - Renault IDE (homogeneous charg



Mercedes



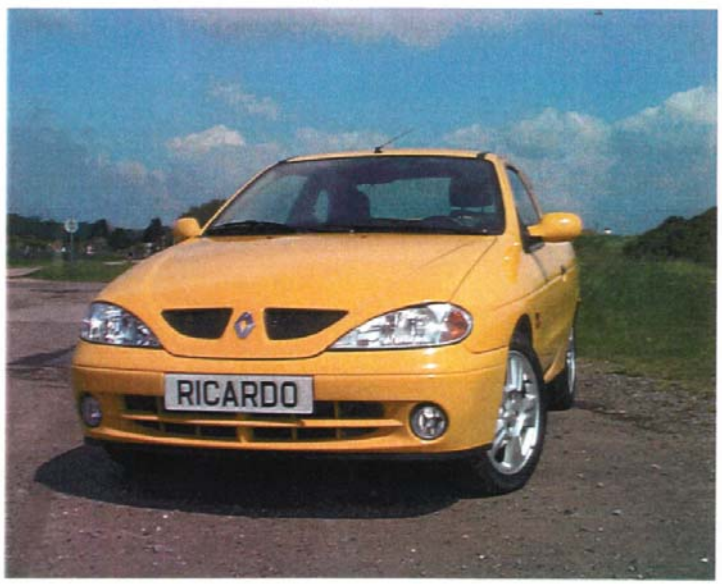
PSA GDI After-treatment technology



- Estimation of NOx based on mathematical model
- Purge with rich fuelling spike
  - Stop when downstream λ sensor shows "rich" - 0.83 initially to purge O_2 change to 0.9 - minimises fuel used

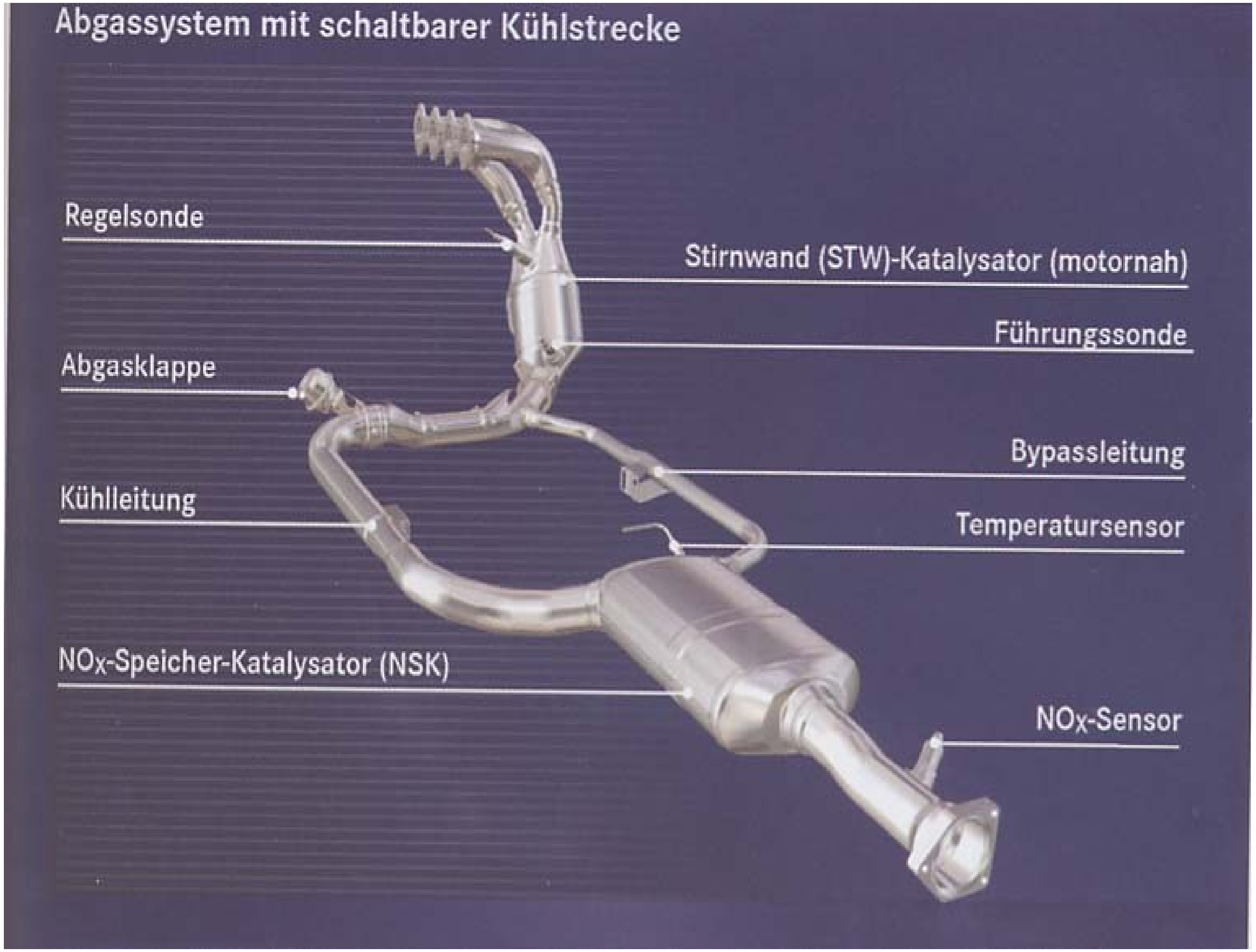
- Upstream and Downstream λ sensors
- 2 x temperature - sensors either side of the pre-cat
  - On Board Diagnostics function of pre-cat (exotherm)
  - LNT temp conversion model estimation
  - NOx purge and DeS
- NOx sensor currently expensive and slow - not used

Applications - Renault F5R engine



- Homogeneous, stoichiometric only combustion system
- Central spark plug and injector
- 2.0L F5R engine applied in Megane passenger car
- 104kW (140PS) and 200Nm at 4250rpm
- EGR
- Close coupled catalyst
- 3-way catalyst
- Meets Euro III and IV emissions standards
- Benchmarked by Ricardo

Mercedes Benz CGI



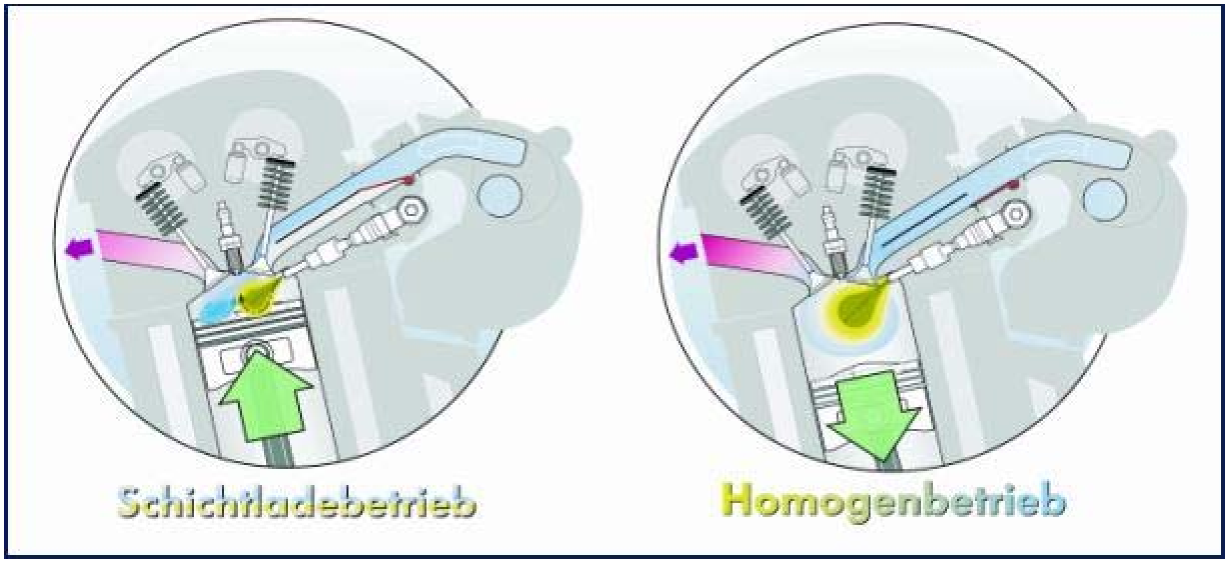
Exhaust system with catalyst bypass.

Close coupled 3-way catalyst

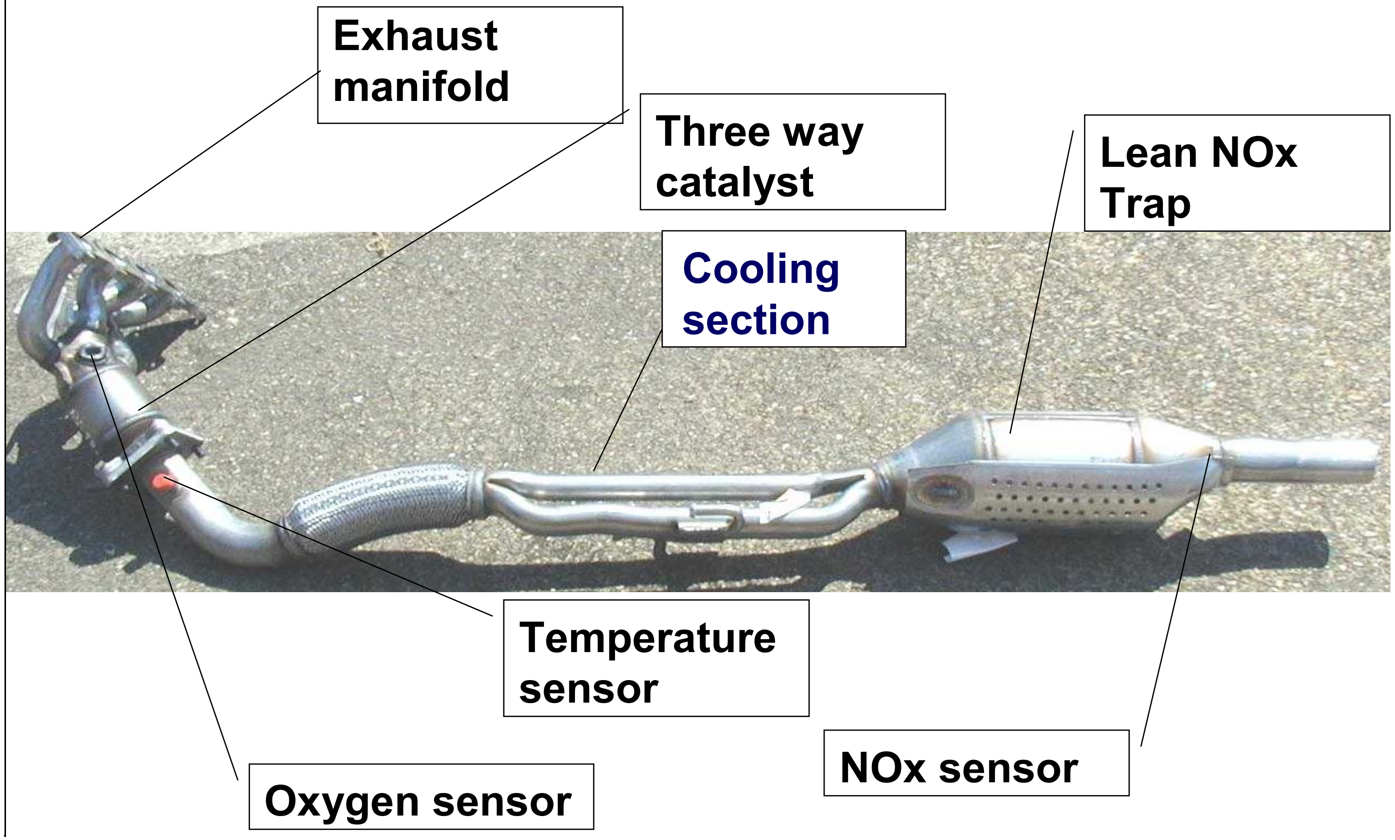
NOx sensor post-NOx storage catalyst

Applications - VW FSI technology

- First European stratified combustion system
  - Stratification of charge enables very lean combustion by mixing in only as much fuel as required
  - Requires direct injection fuel system
- 1.4L FSi engine applied in Lupo passenger car
- 77kW (105PS) and 130Nm at 4250rpm whilst meeting Euro IV
- NOx sensor used with Lean NOx Trap

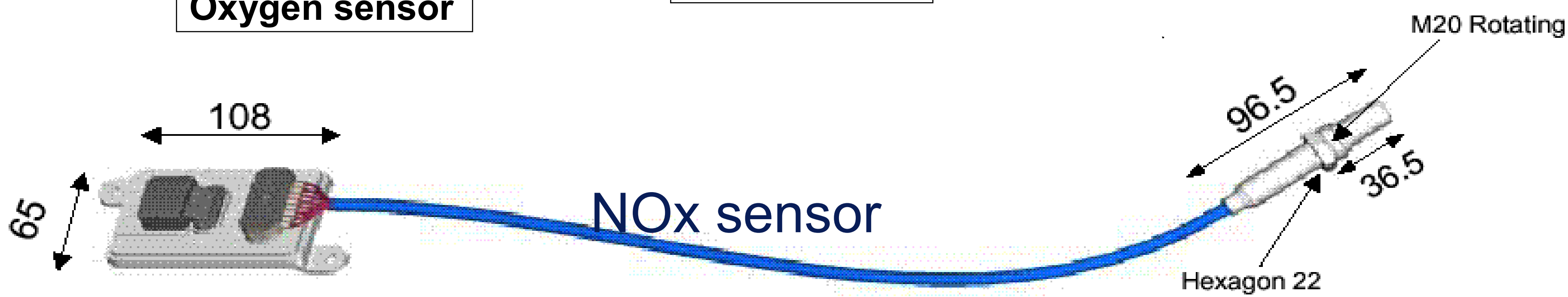


VW FSI Lupo system

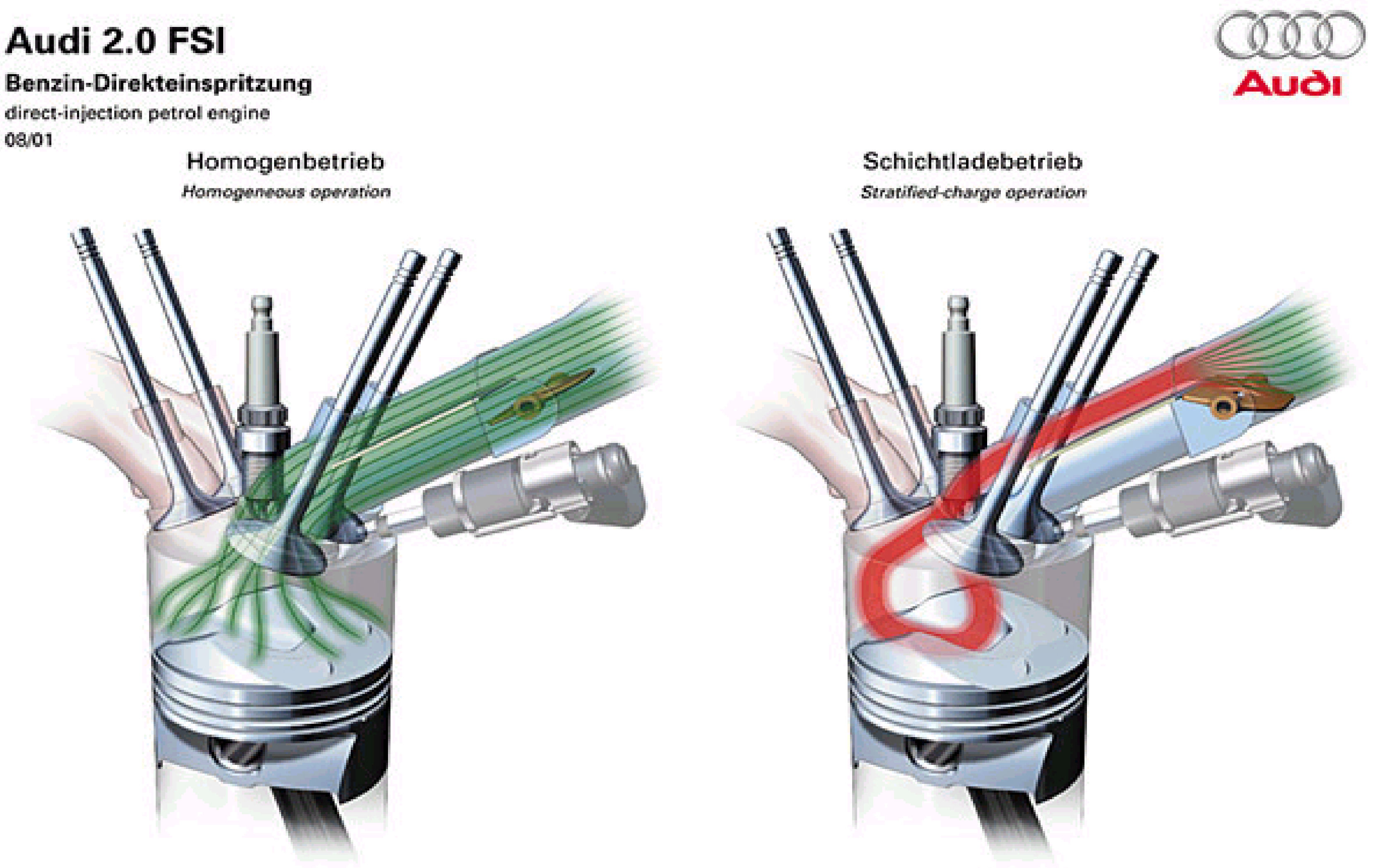


Catalyst: DMC^2 + JM

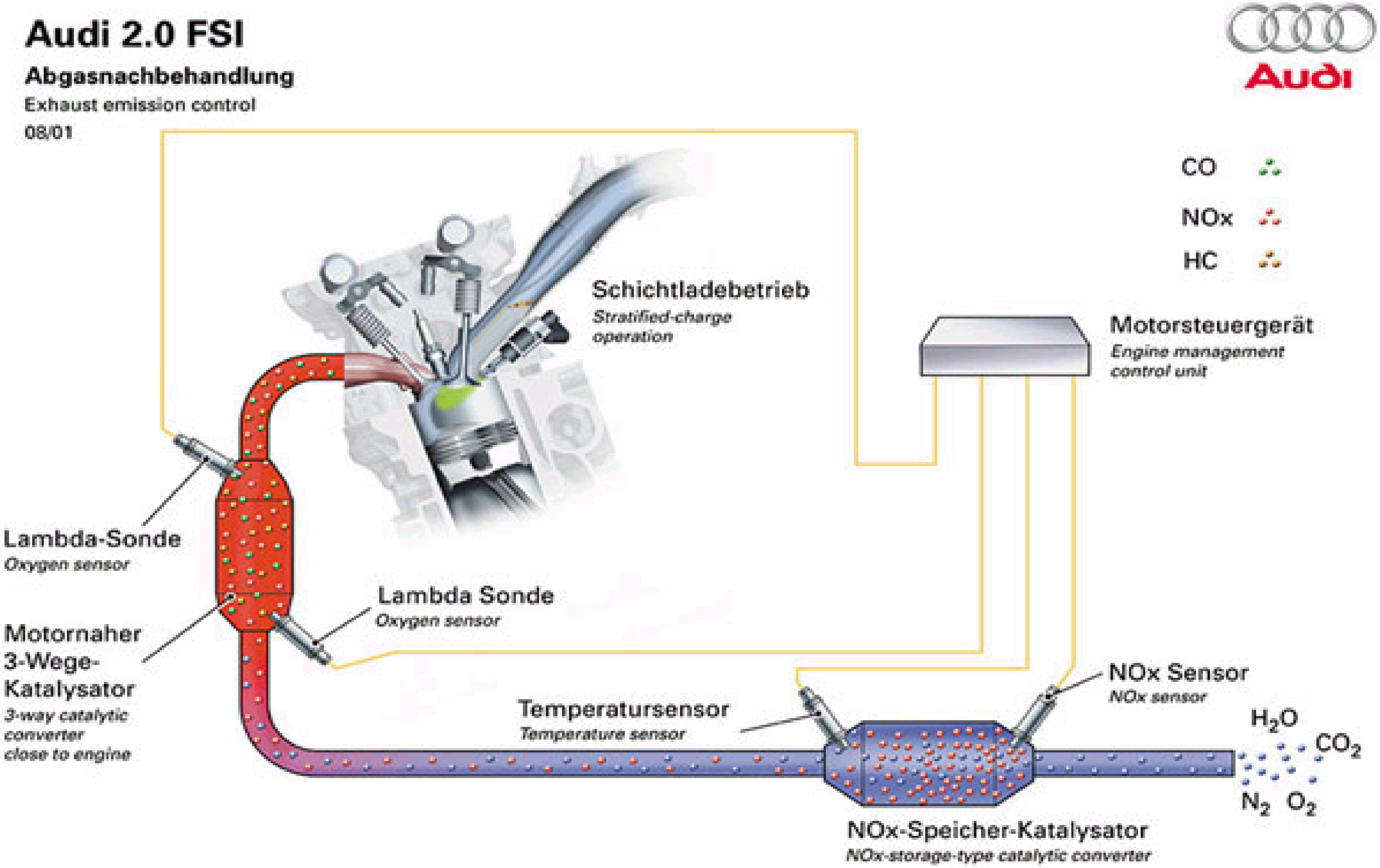
Control: Bosch



Applications - Audi FSI 2.0L

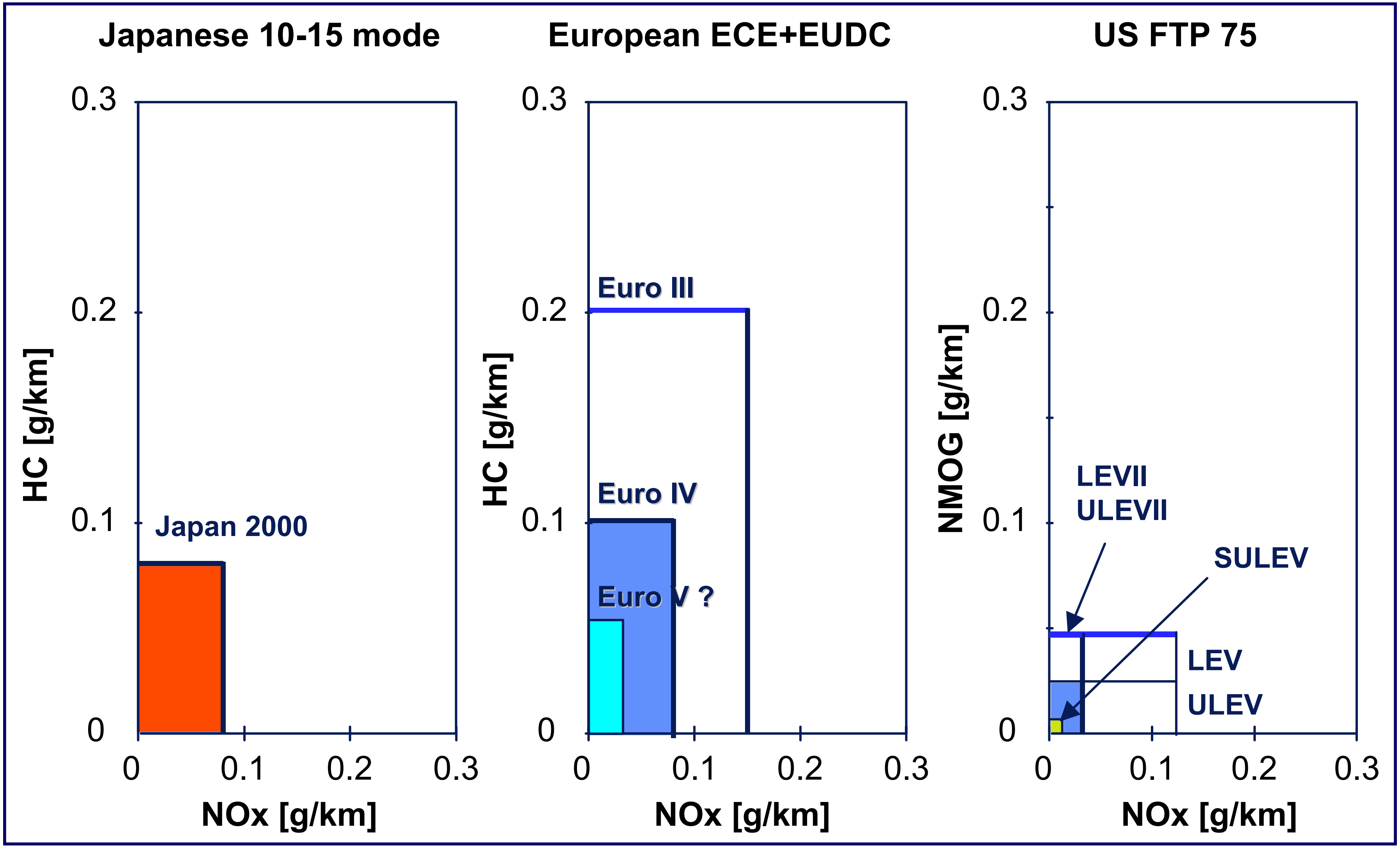


Audi FSI 2.0L



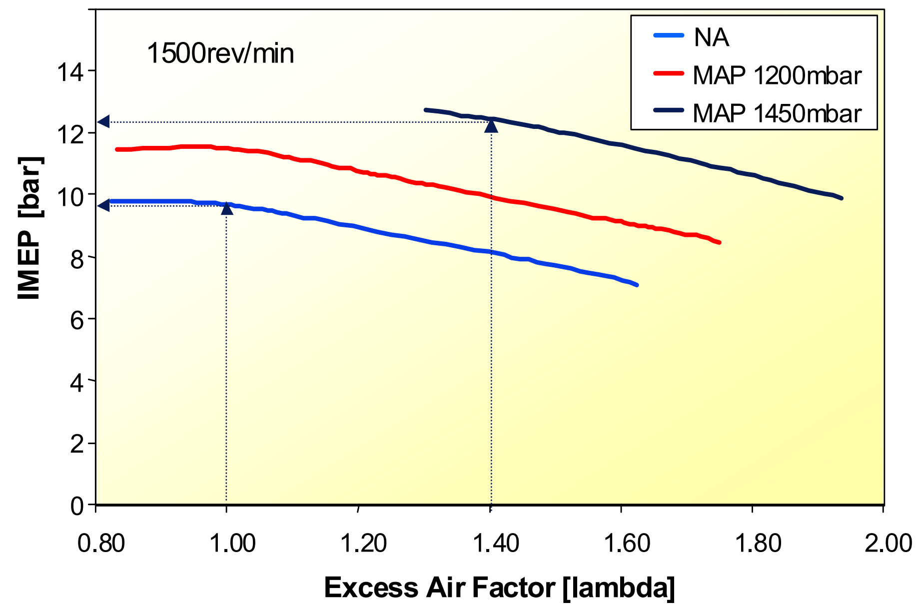
Audi 2.0 FSI
Abgasnachbehandlung
Exhaust emission control
08/01
Audi
CO
NOx
HC
Schichtladebetrieb
Stratified-charge operation
Motorsteuergerät
Engine management control unit
Lambda-Sonde
Oxygen sensor
Lambda Sonde
Oxygen sensor
Motornaher 3-Wege-Katalysator
3-way catalytic converter close to engine
Temperatursensor
Temperature sensor
NOx Sensor
NOx sensor
H_2O
CO_2
N_2
O_2
NOx-Speicher-Katalysator
NOx-storage-type catalytic converter

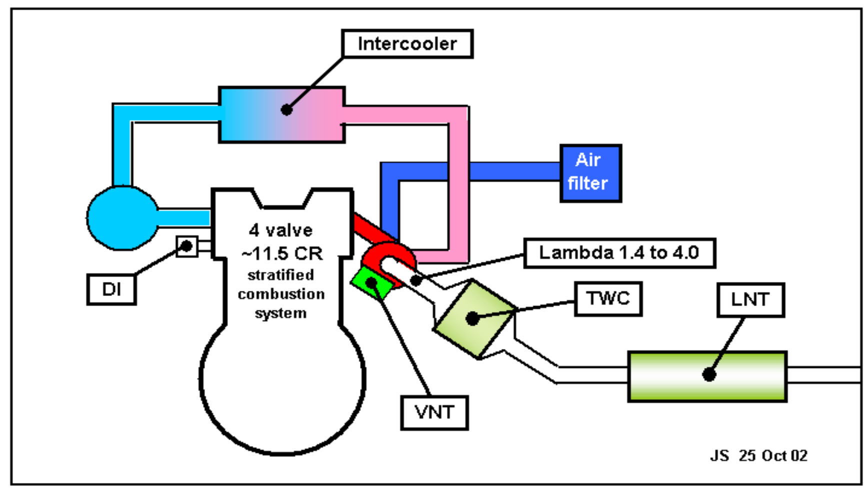
Comparison of Emission Standards for Gasoline Engines



Ricardo "Lean Boost" GDI engine concept

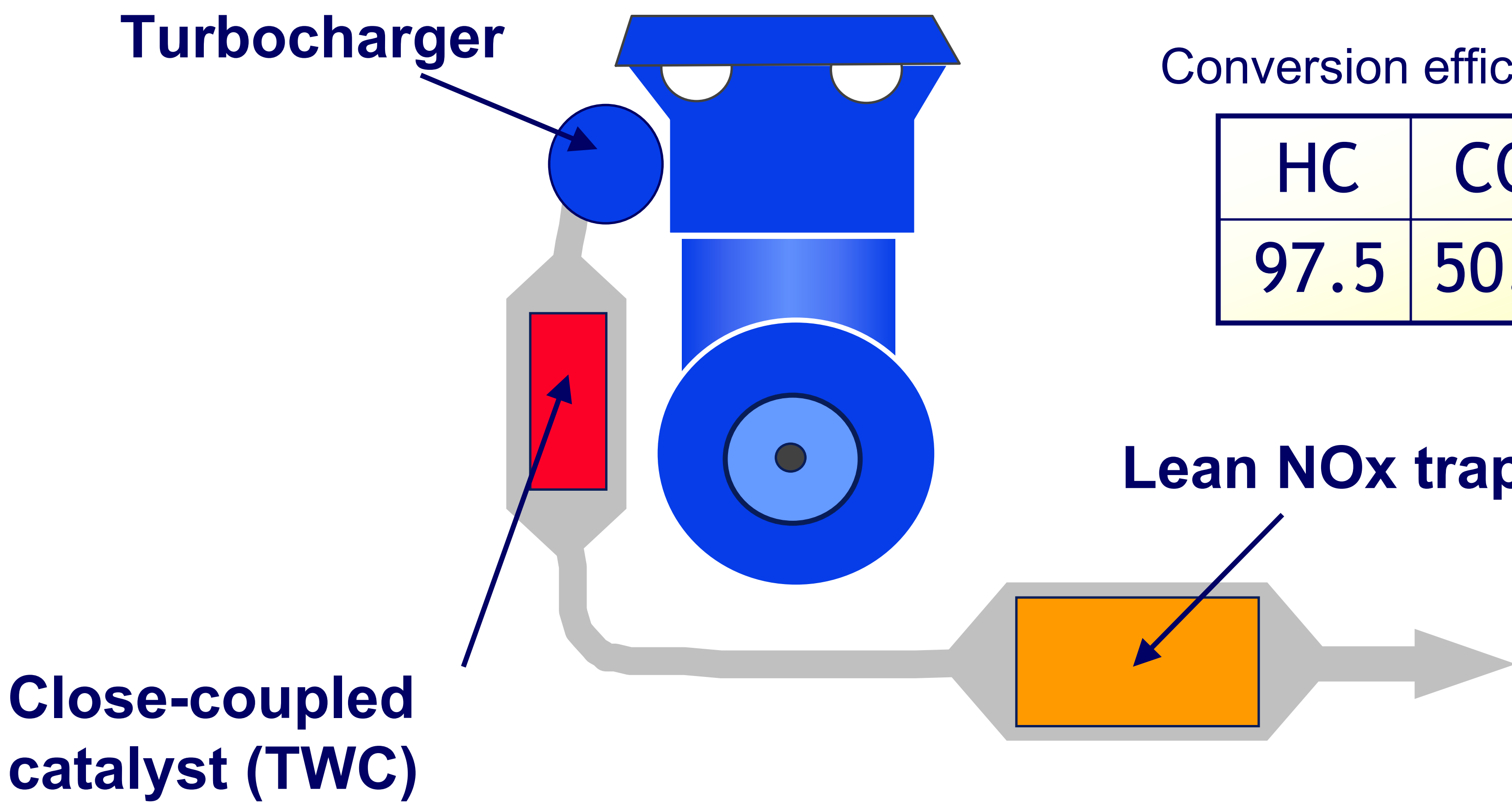
- Ricardo research program for last 4 years
- Octane requirement controlled by
  - direct injection
  - lean operation at full load ($\lambda = 1.4$)
  - late injection lean stratified operation at part load
- Downsize factor limited by low speed torque
  - LBDI at 1500 rpm 11.9 bar BMEP
  - NA engine at 1500 8.8 bar BMEP
  - Downsize factor 11.9/8.8=1.35
  - Base 1.6 litre engine can be replaced by 1.18 LBDI
  - Ricardo study based on 1.125 litre
- Low exhaust temperature allows use of a diesel-type variable nozzle turbine for improved low speed torque and transient response





Ricardo "Lean Boost" GDI aftertreatment system

- Lean NOx Aftertreatment



Euro IV - C class vehicle

Conversion efficiencies [%]

HC	CO	NOx
97.5	50.3	89.6

Ricardo "Lean Boost" GDI NEDC drive cycle simulation

- Lean Boost C class vehicle NEDC drive cycle simulation results

	CO2 (g/km)
1.6 litre NA (homologation)	169
Baseline t/c 1.125 litre 3-cyl	154.1
Lean Boost 1.125 litre 3-cyl	132.2

↓ 8.8% (1.6 litre NA to Baseline t/c)
↓ 14.2% (Baseline t/c to Lean Boost)
↓ 21.8% (1.6 litre NA to Lean Boost)

- On drive cycle, regeneration allowance can be 0% (passive regeneration) to 1% (more typical)
- Hence LBDI >20% better than baseline
- Euro IV emissions levels can be achieved

Example of GDI Controls System: Bosch

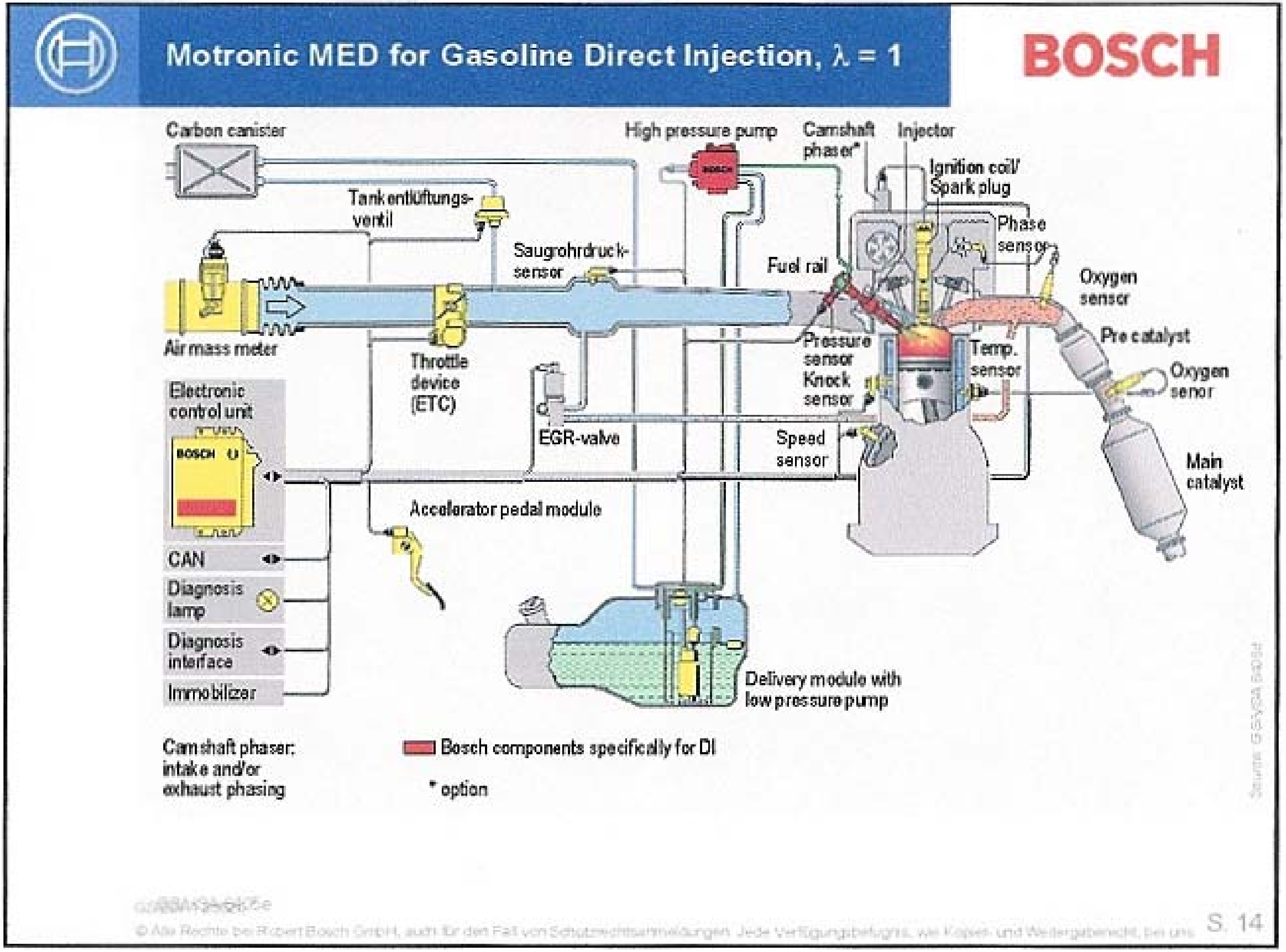
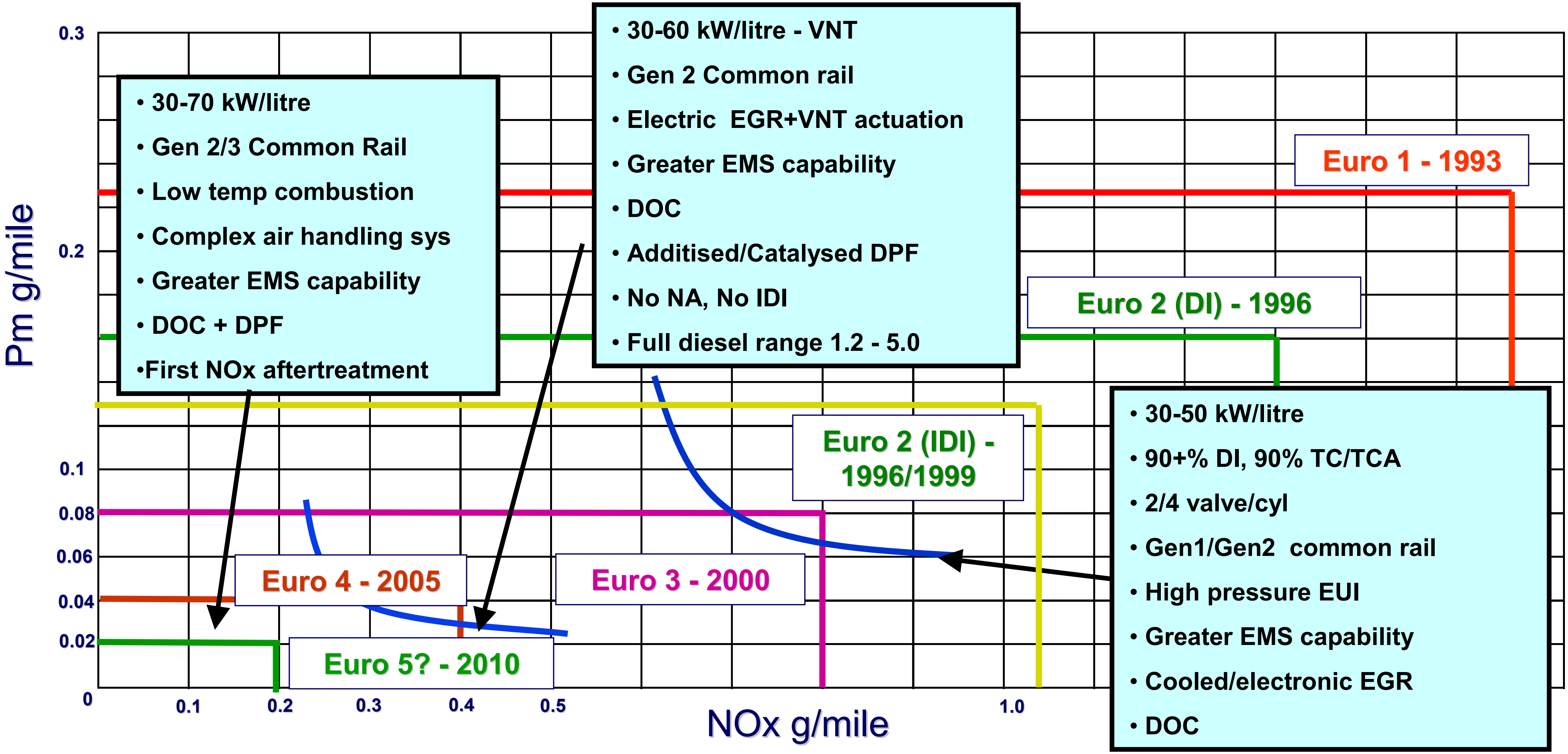


Diagram shows layout of control equipment for stoichiometric engines

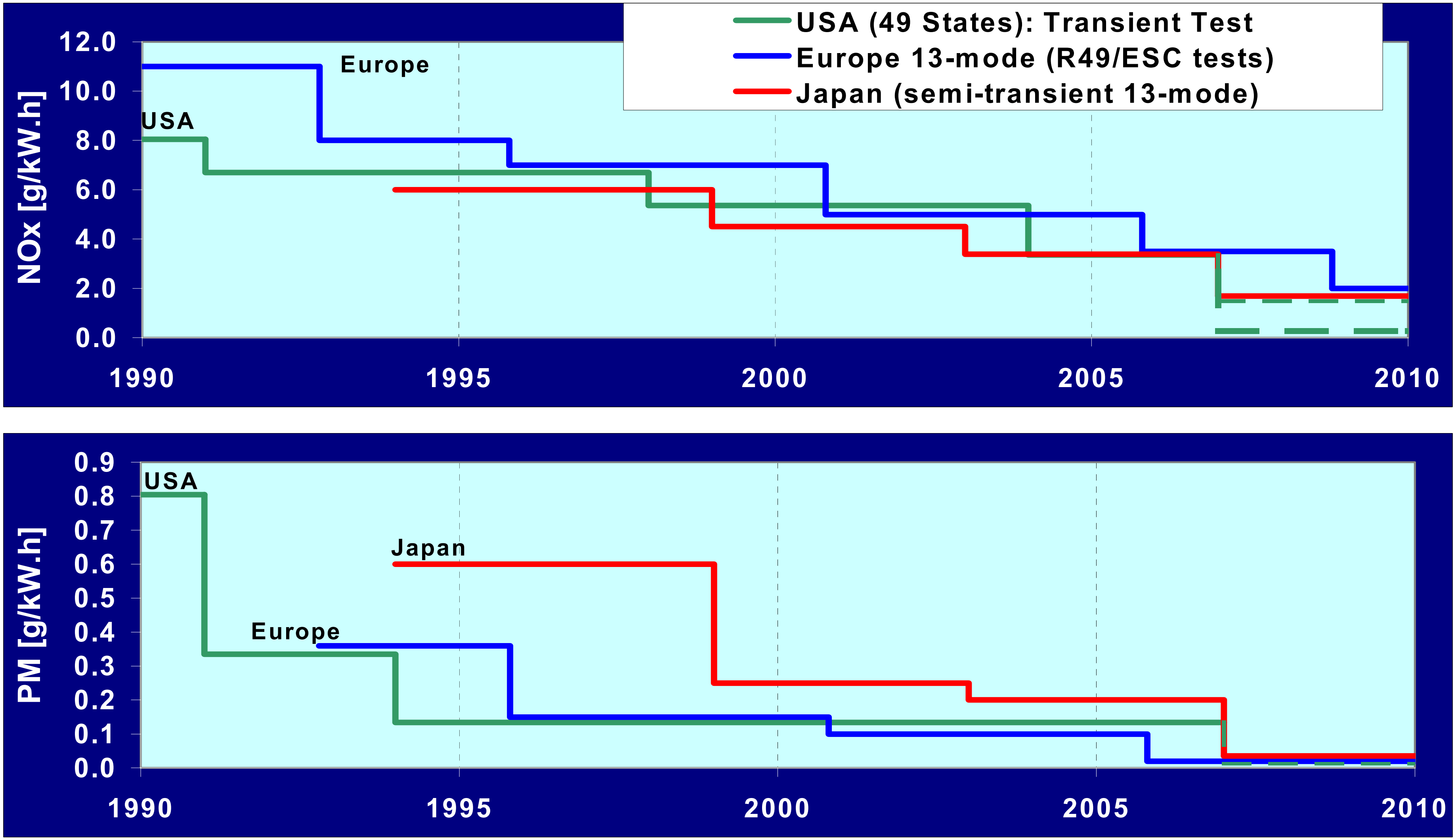
Background Information: Diesel Engine Technology

1993-2010: European diesel legislation continues to push technology

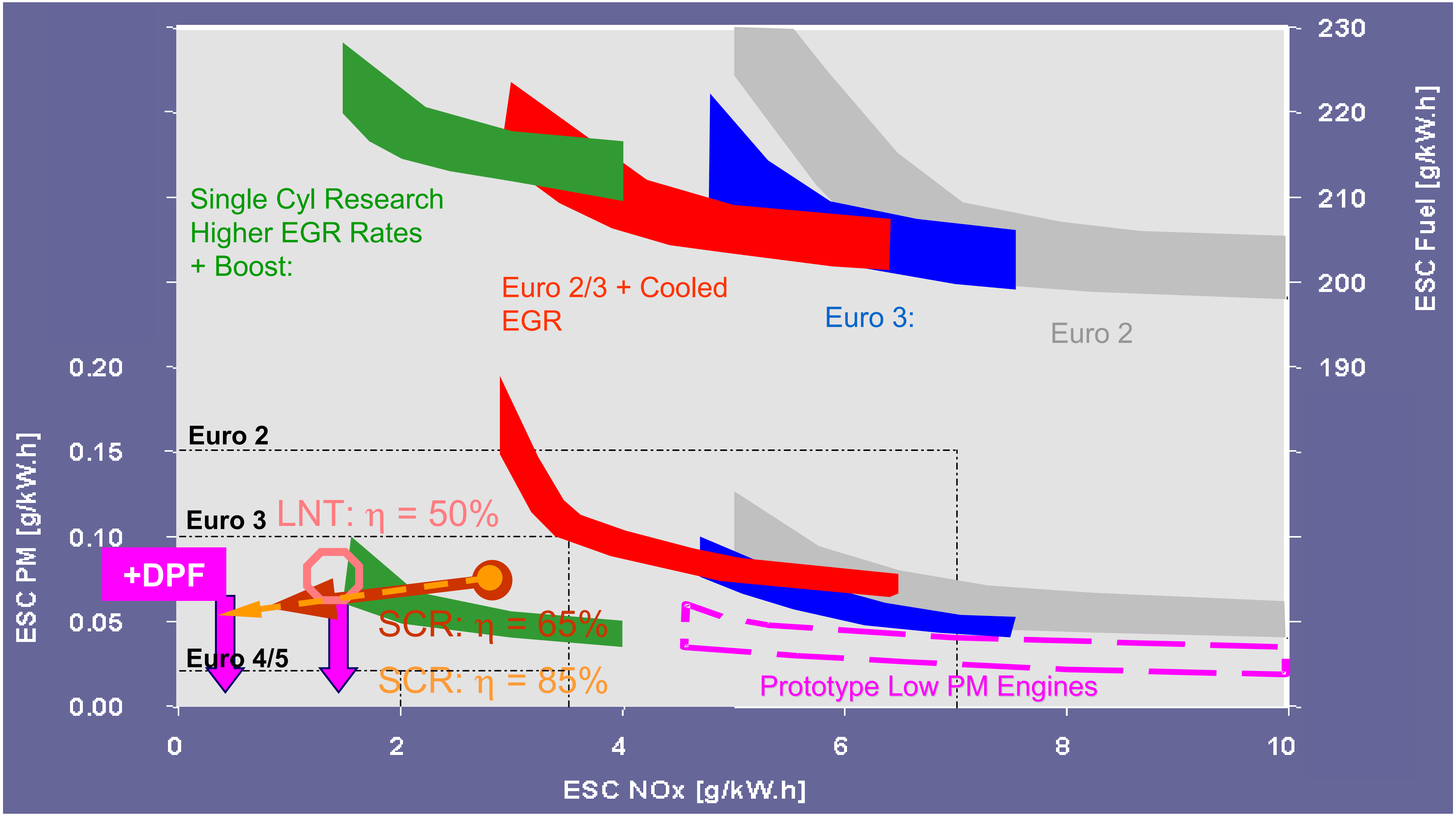
- European legislation has evolved to continually push forward technology
- Test definition made more stringent in parallel with reduced limits



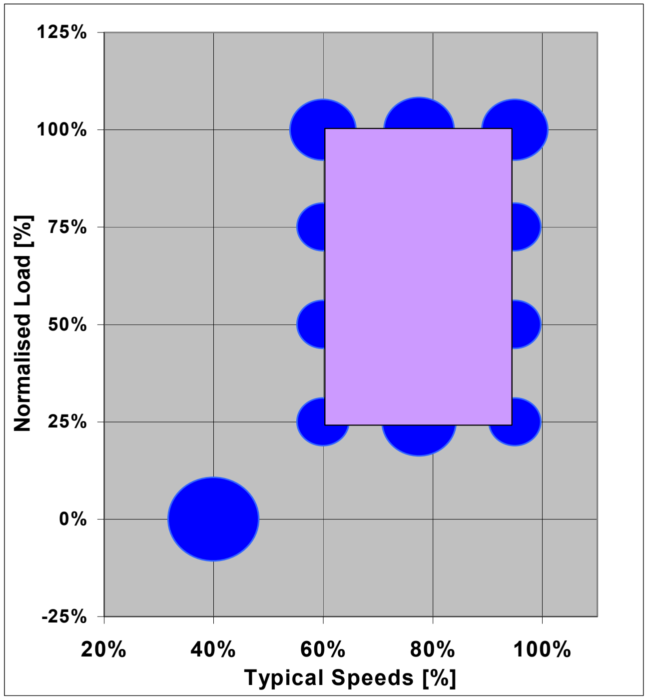
Exhaust Emissions Legislation

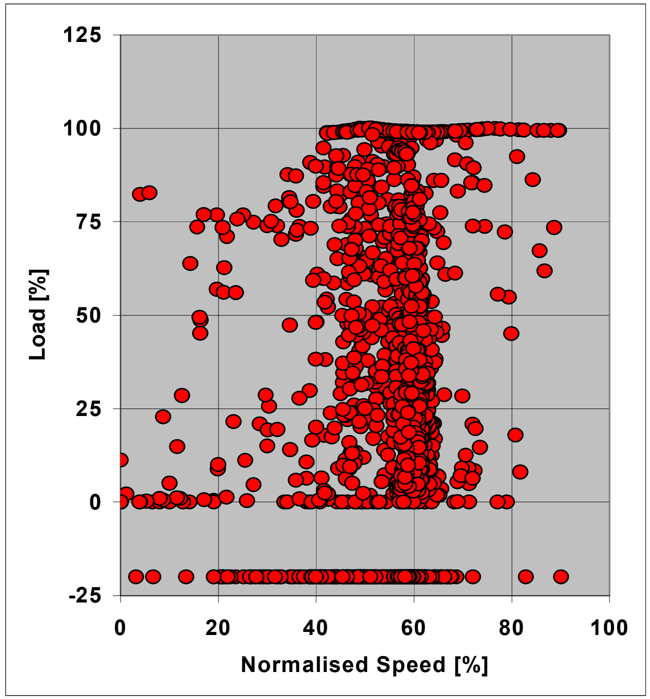


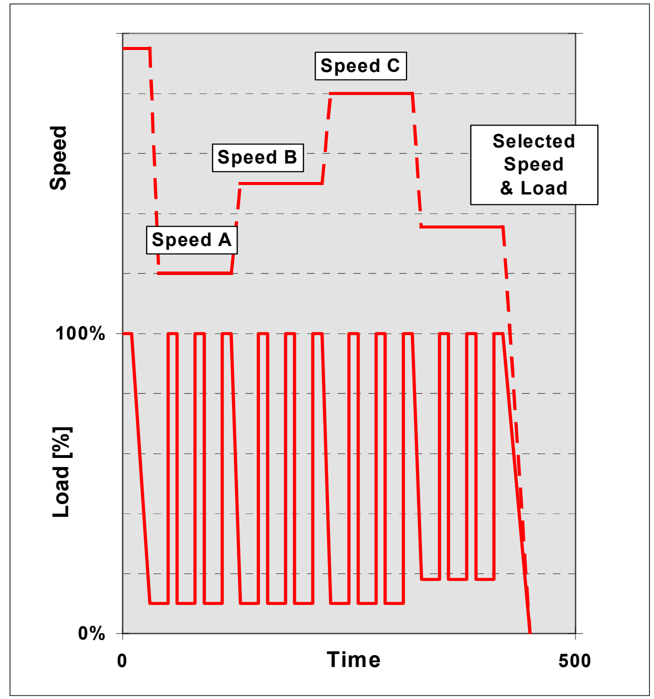
Heavy Duty Emissions Legislation (ESC Test)



HD Diesel Test Cycles - Europe





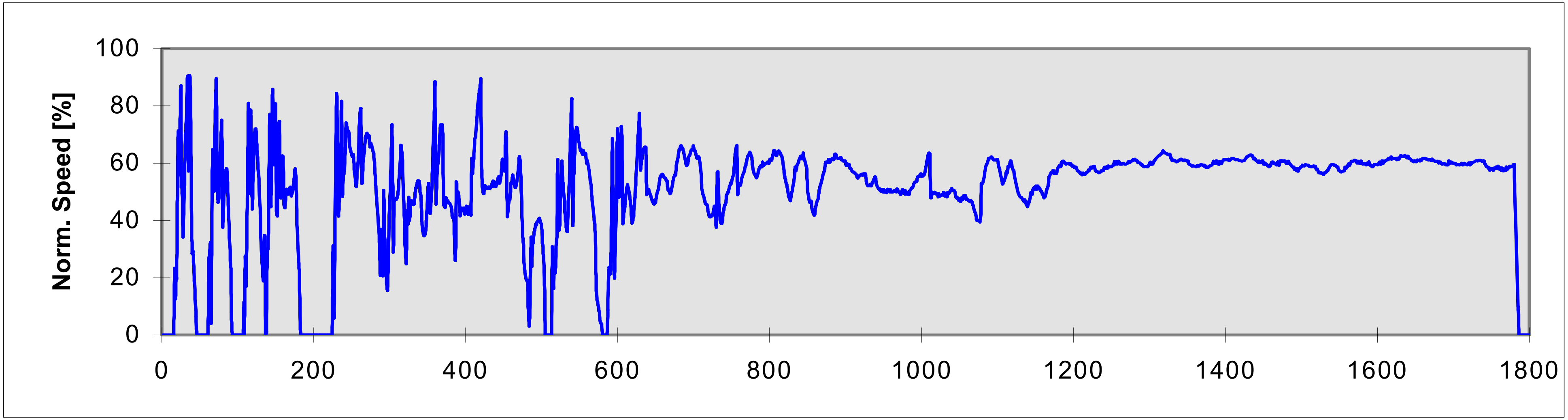


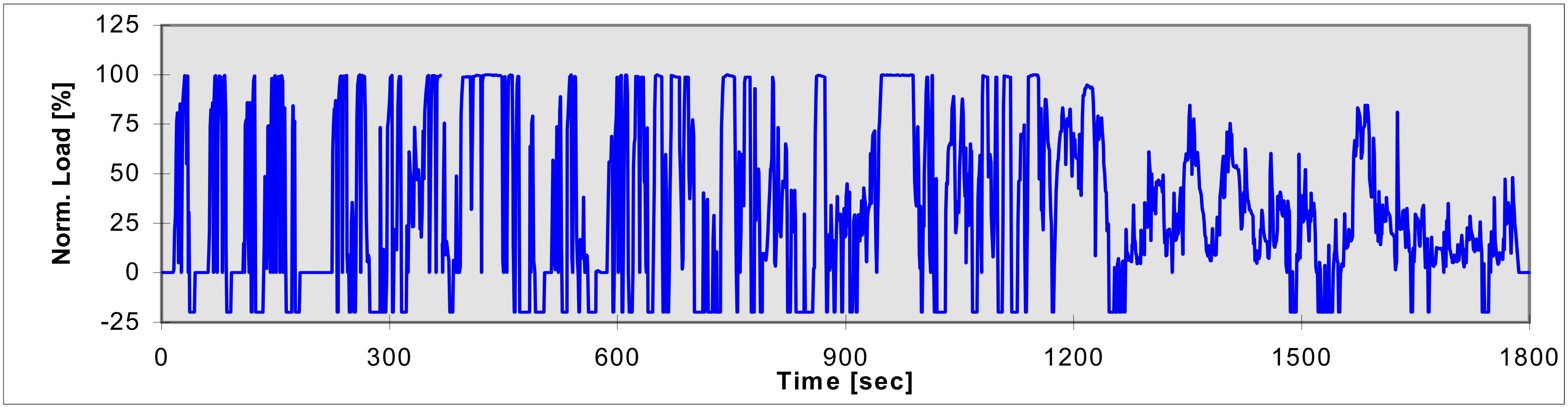
European Steady-state Cycle (ESC)

European Transient Cycle (ETC)

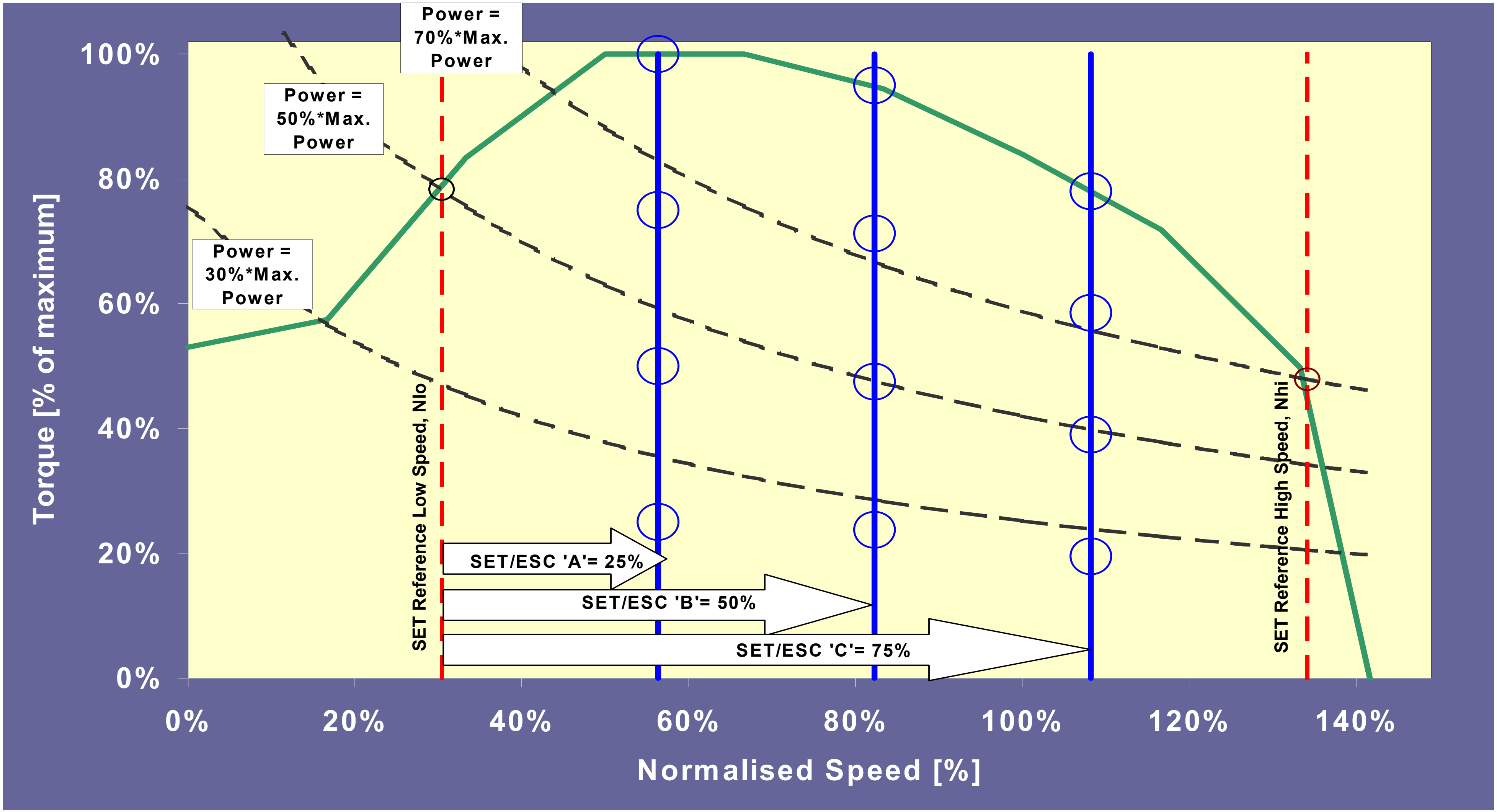
European Load Response (ELR) Smoke Test

European ETC Test
Speed & Load

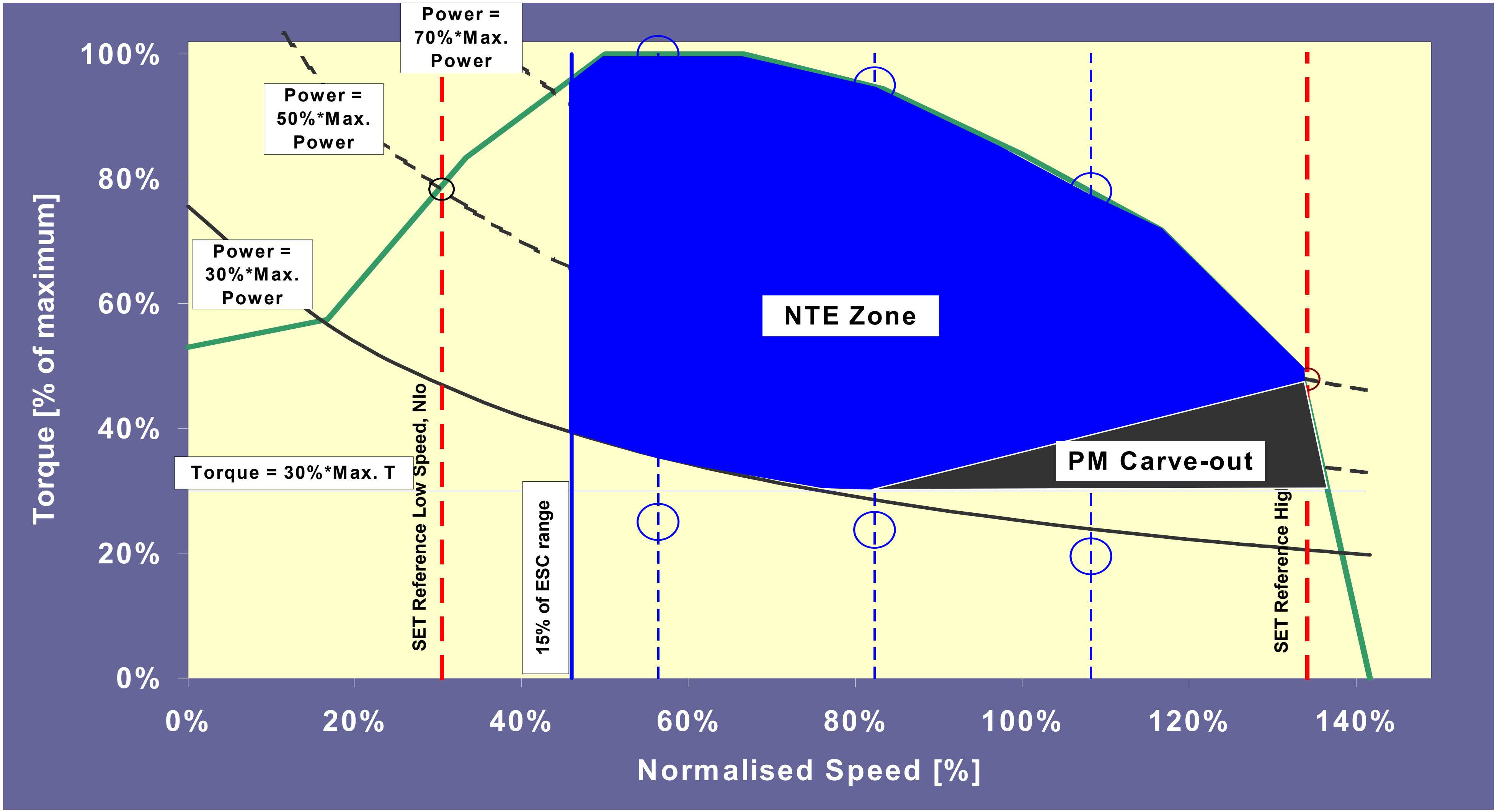




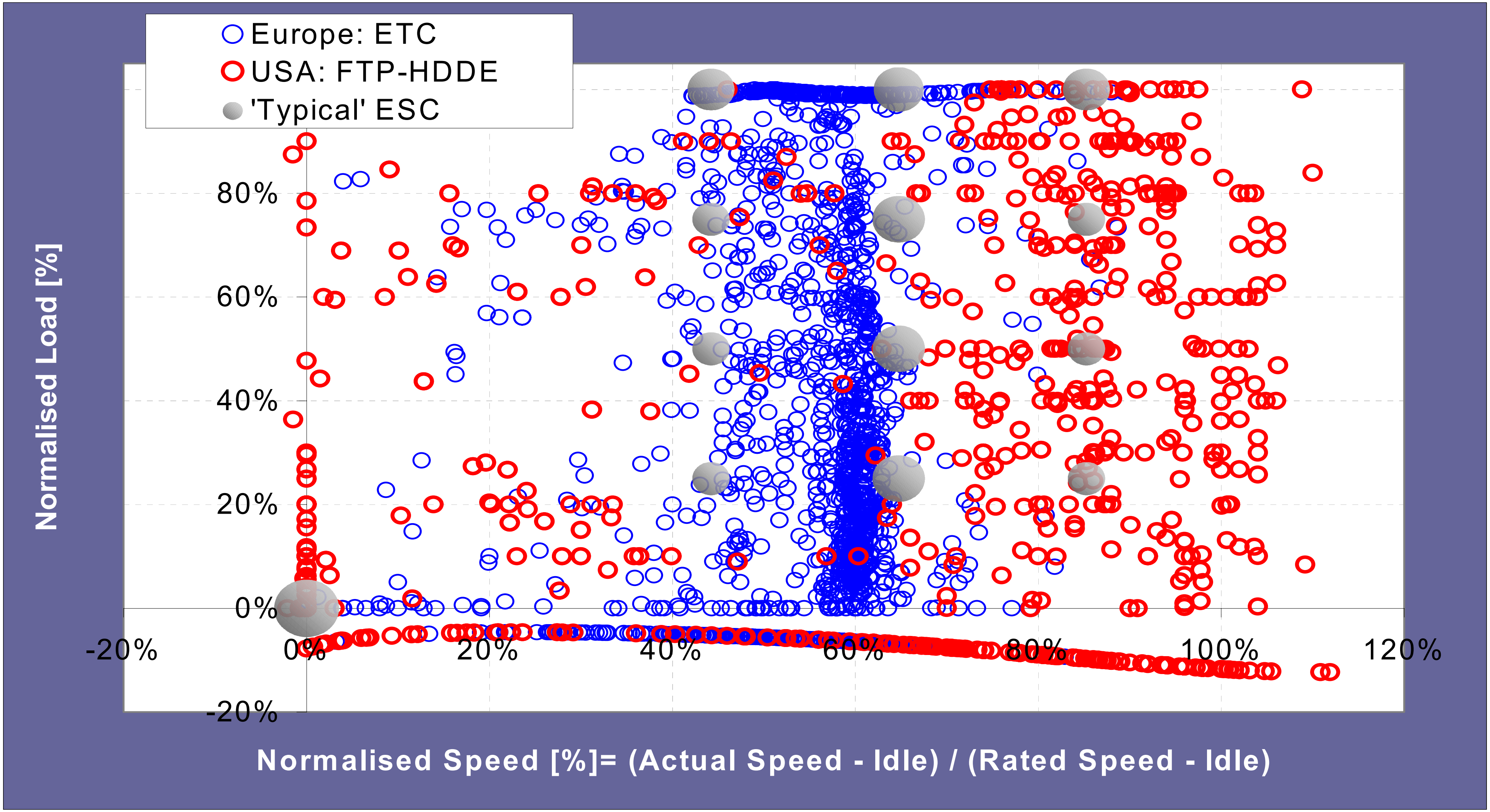
Definitions: SET Test: The reference speeds are determined at 50% (Nlo) and 70% (Nhi) of max.power. Test speeds are at 25%, 50% & 75%



Definitions: NTE Zones: Zone is bounded by Speed: ESC15%, Power: >30% , Torque: >30% Carve-out" for PM at high speed



Heavy Duty exhaust emissions test cycles: Cover much of the engine operating range



Features of Heavy Duty Diesel Fuel Injection Technologies

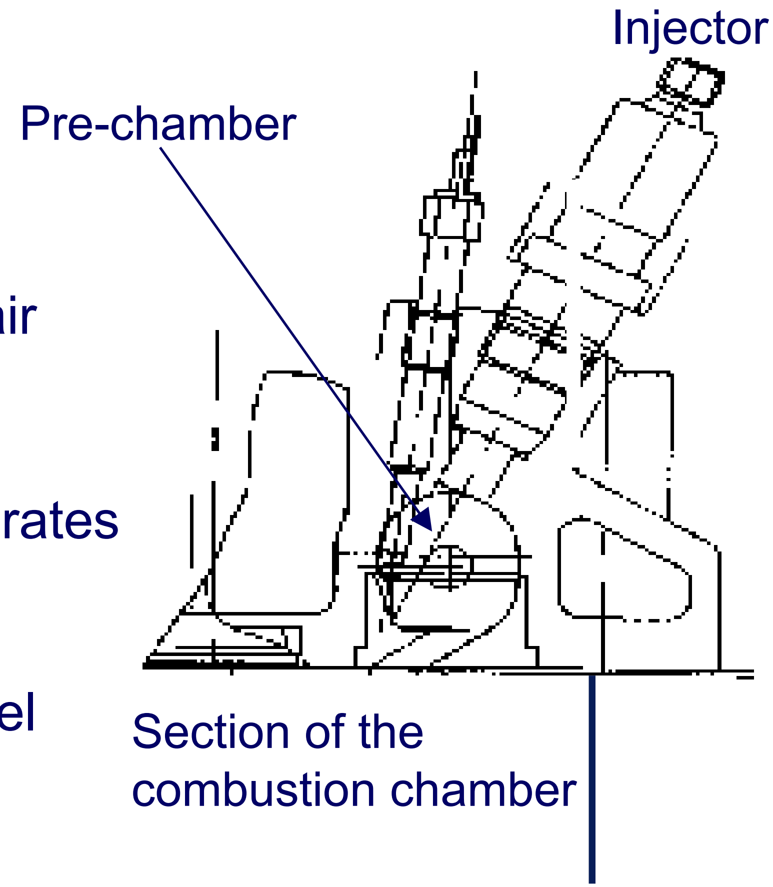
	Euro 3	Euro 4	Euro 5
PM (ESC/ETC) [g/kW.h]	0.10/0.16	0.02/0.03	0.02/0.03
NOx [g/kW.h]	5.0	3.5	2.0
Technologies	Combustion Optimisation & Timing Retard or EGR	EGR+PM_Trap or SCR(+PM_Trap?)	SCR(+PM_Trap?) or EGR+PM_Trap
Common Rail	Yes	Yes	Yes
Maximum Pressure [bar]	1400-1600	1600-1800	1600-2000
Flexible Pressure Control	Required	Required	Required
Pilot Injection	Available	Available	Available
Flexible Pilot Capability	Desirable	Desirable	Desirable
Initial Rate Control	Preferred - not available?	Desirable - possible?	Desirable - available?
Post Injection	Desirable - available?	Required - available	Required - available
Pump Drive Torque	Low/Even	Low/Even	Low/Even
EUI/EUP	Yes	Yes	Yes
Maximum Pressure [bar]	1600-1800	1800-2000	1600-2200
Flexible Pressure Control	Not available	Desirable - available?	Required
Pilot Injection	Available	Available	Available
Flexible Pilot Capability	Limted Capability	Desirable	Desirable
Initial Rate Control	No (Delta Pressure Diagram)	Desirable - possible?	Desirable - available?
Post Injection	Not essential	Requirement - To be confirmed	Requirement - To be confirmed
Pump Drive Torque	High Peak Torques	High Peak Torques	High Peak Torques
Rotary Pumps	Possible (under ~250 hp)	Possible (under ~250 hp)	Unlikely
Maximum Pressure [bar]	1800	1800-1850	2000?
Flexible Pressure Control	Not available	Not available	Not available
Pilot Injection	Limted Capability	Limted Capability	Limted Capability
Initial Rate Control	Available	Available	Available
Post Injection	Limted Capability	Limted Capability	Limted Capability
Pump Drive Torque	Medium-High Peak Torques	Medium-High Peak Torques	High Peak Torques

Technology Requirements with Increasing Emissions Severity

- As emissions legislation increased in severity, higher injection pressures were required for smoke control
- With the increase in pressure, the droplet velocity is increased and thus less swirl is required to provide the shearing action for evaporation
- With higher pressures, the penetration increases with re-entrant chambers such that the nozzle specification required to avoid spray overlap starts to benefit the use of open chambers with low swirl for heavy duty whilst light duty remains re-entrant
- Lower swirl reduces heat transfer and thus improves fuel economy
- Beyond these emissions requirements, the level of retard required for NOx control leads to increases in fuel consumption such that alternate means of NOx control such as EGR or SCR are considered
- EGR requires an increase in swirl for EGR mixing and higher boost pressures for air/fuel ratio compensation
- SCR requires no fundamental change to the combustion system other than consideration of the fuel spray path at more advanced timings now possible

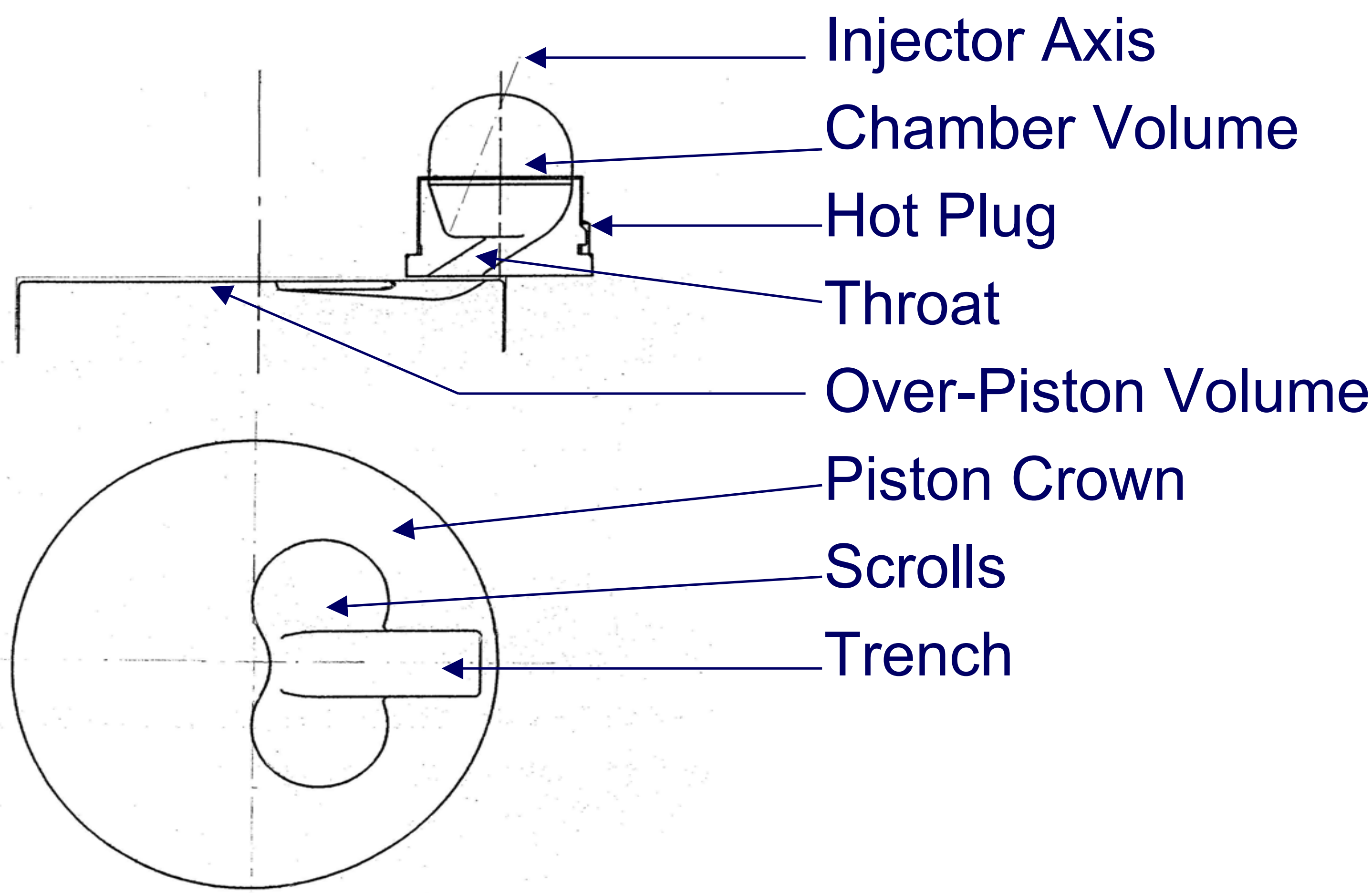
In-Direct Injection (IDI)

- Key advantages
  - Low cost compared to DI engines
    - Lower pressure fuel injection equipment (~150bar)
  - Small displacement
  - Low noise
- Principals
  - Compression stroke; air pushed into “pre-chamber” through small port, creating rapid air motion
  - Combustion stroke; fuel is injected into pre-chamber. Rapid air motion mixes and evaporates fuel, which ignites under the pressure. The mixture rapidly expands out into the main combustion chamber where the remaining fuel burns as it mixes with air



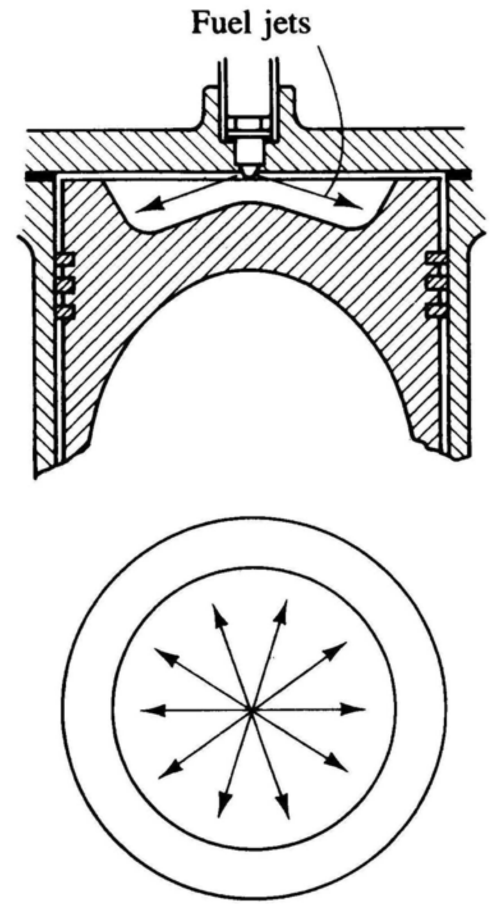
Main Features of Ricardo "Comet" Combustion System

By far the most popular IDI combustion system



Features of Direct Injection (DI)

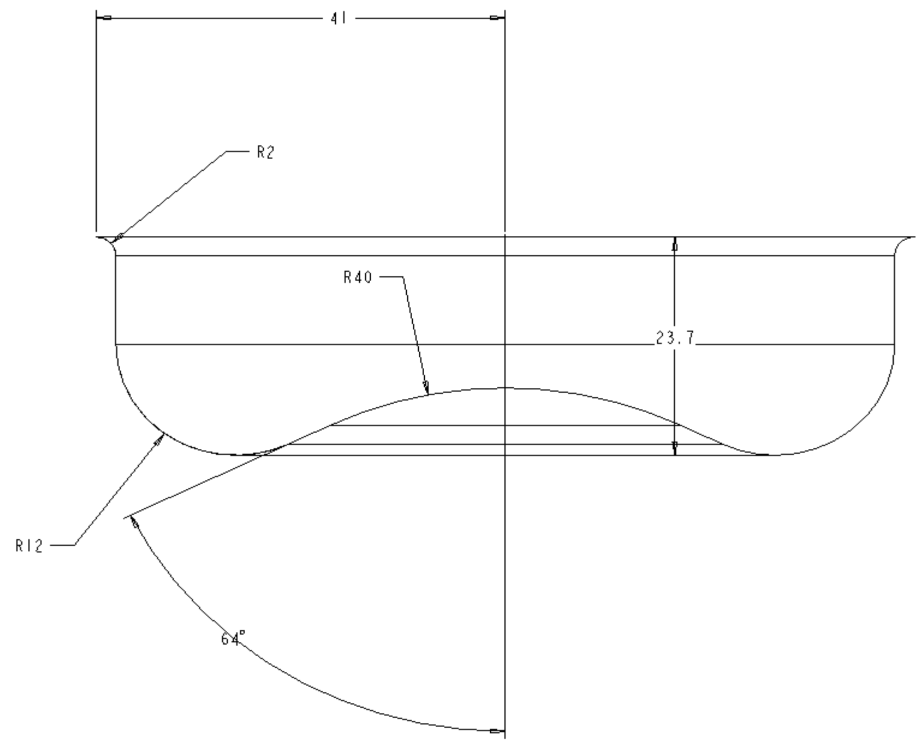
- Direct injected engines inject fuel directly into the combustion chamber
- Key feature is improved fuel economy
  - Losses associated with pushing air in and out of a pre chamber are eliminated
- However costs are increased because of
  - Higher fuel pressures (~1100 increasing to 2000 bar to meet successive emissions requirements)
  - Revised injector designs with multiple and increasingly small holes
- Costs further increased as mechanical diesel injection pump eventually replaced by common rail or unit injection pump systems
  - However these have the advantage of allowing better control and multiple injection events



Extracted from “Internal Combustion Engine Fundamentals”, John B. Heywood, McGraw Hill

Combustion Chamber Design: Generic Profile of Open Chamber

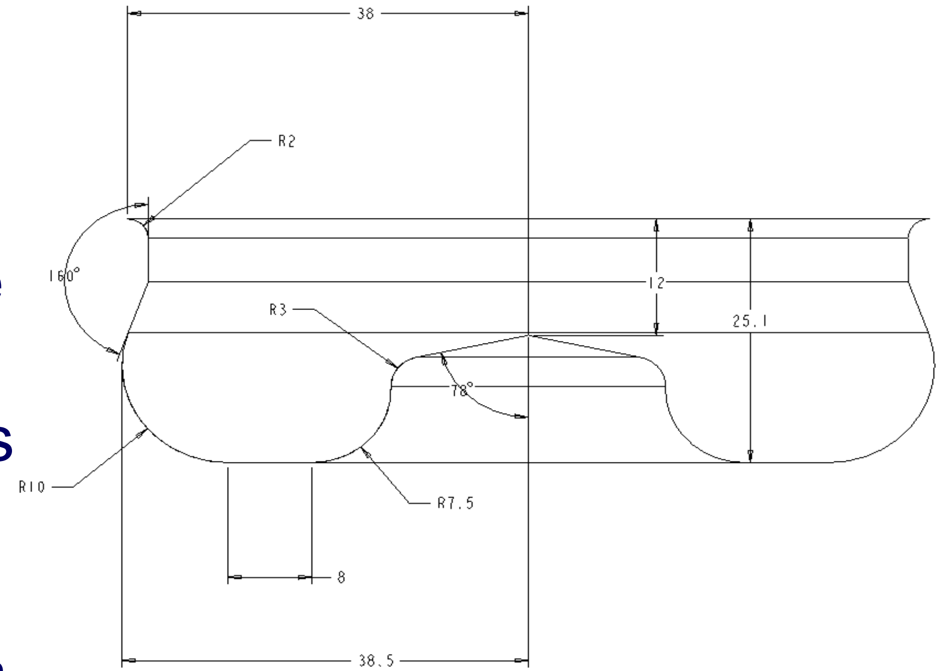
- Open Chambers enable low inlet swirl ratios to be used
- Nozzle matching is more predictable
- Require high fuel pressures for minimum Pm
- Potential for lowest fuel consumption
  - No “throat” losses



Generic chamber shape only: details of performance of selected FIE system needed for more definitive shape

Combustion Chamber Design: Generic Profile of Re-entrant Chamber

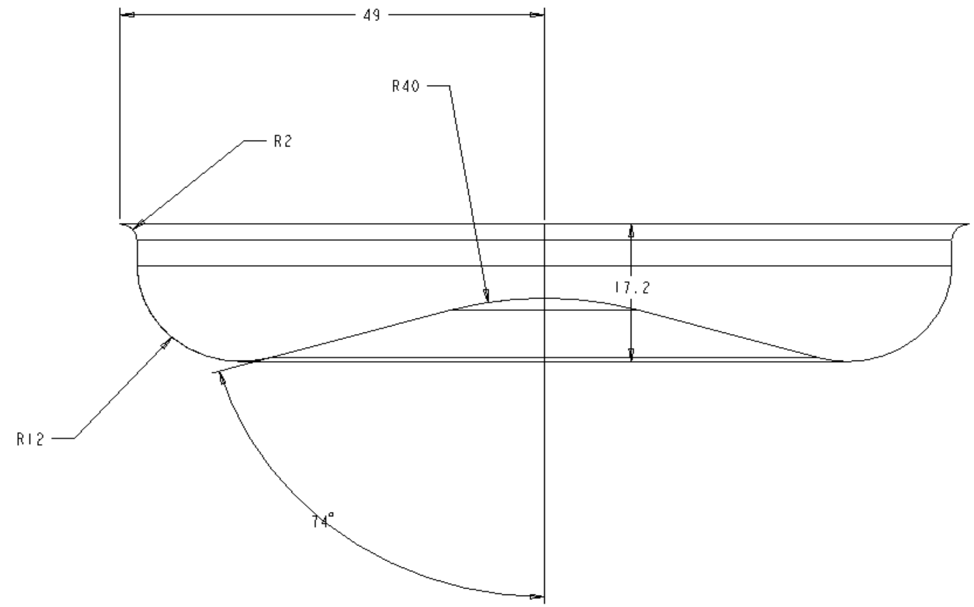
- Tend to reduce smoke at retarded timings
- Very low Pm achievable at more moderate fuel pressures
- Optimise with narrow nozzle cone angles
- Require moderate inlet swirl ratios (1.6~2.0 Rs), even with high pressure FIE (>1400 bar)
- Thermal loading of piston crown a concern, especially with larger bore sizes and high BMEPs
- Common rail FIE matches re–entrant chambers well



Generic chamber shape only: details of performance of selected FIE system needed for more definitive shape

Combustion Chamber Design: Generic Profile of Wide Open Chamber

- This shape is generally associated with on-road engines using fuel pressures > 1500 bar
- Wider open chambers often compatible with lowest swirl ratios and EUI FIE
- Concerns about overspray of fuel at retarded injection timings

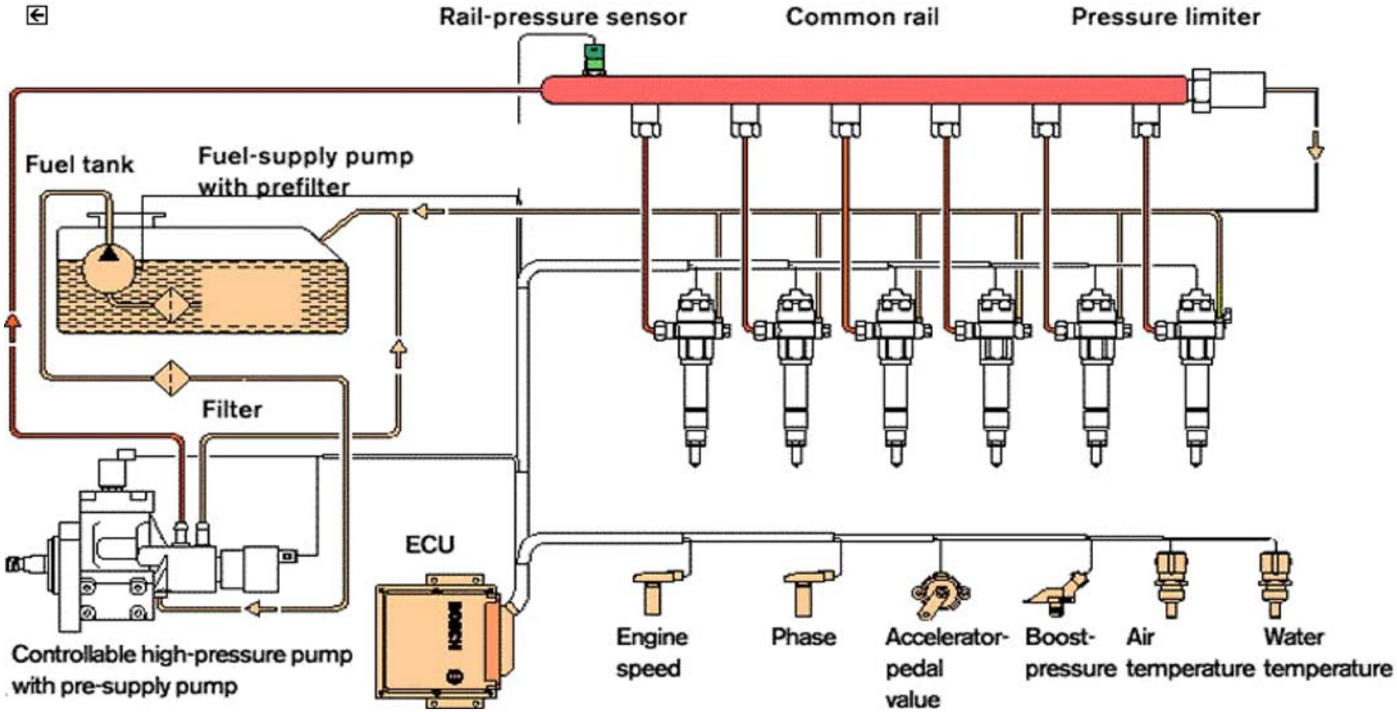


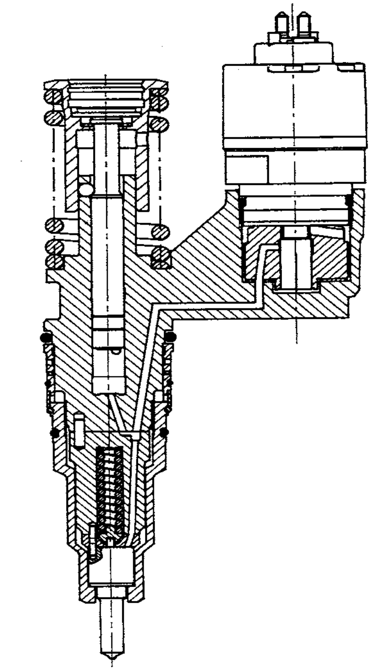
Generic chamber shape only: details of performance of selected FIE system needed for more definitive shape

Fuel Injection Systems: Rotary Diesel Injection Pump

- Baseline equipment for most light duty diesel applications for engines with both in-direct and direct injection combustion systems (left hand picture)
- Initially fully mechanical, these were redesigned for electronic control (right hand picture)
- Basically works by
  - A small amount of fuel is compressed in a cylinder
  - Shock waves pass along the injector feed pipe as pressure builds
  - Pressure quickly rises to the point where the injector spring is overcome and fuel is released into the combustion chamber

Fuel Injection Systems: Common Rail and Electronic Unit Injector

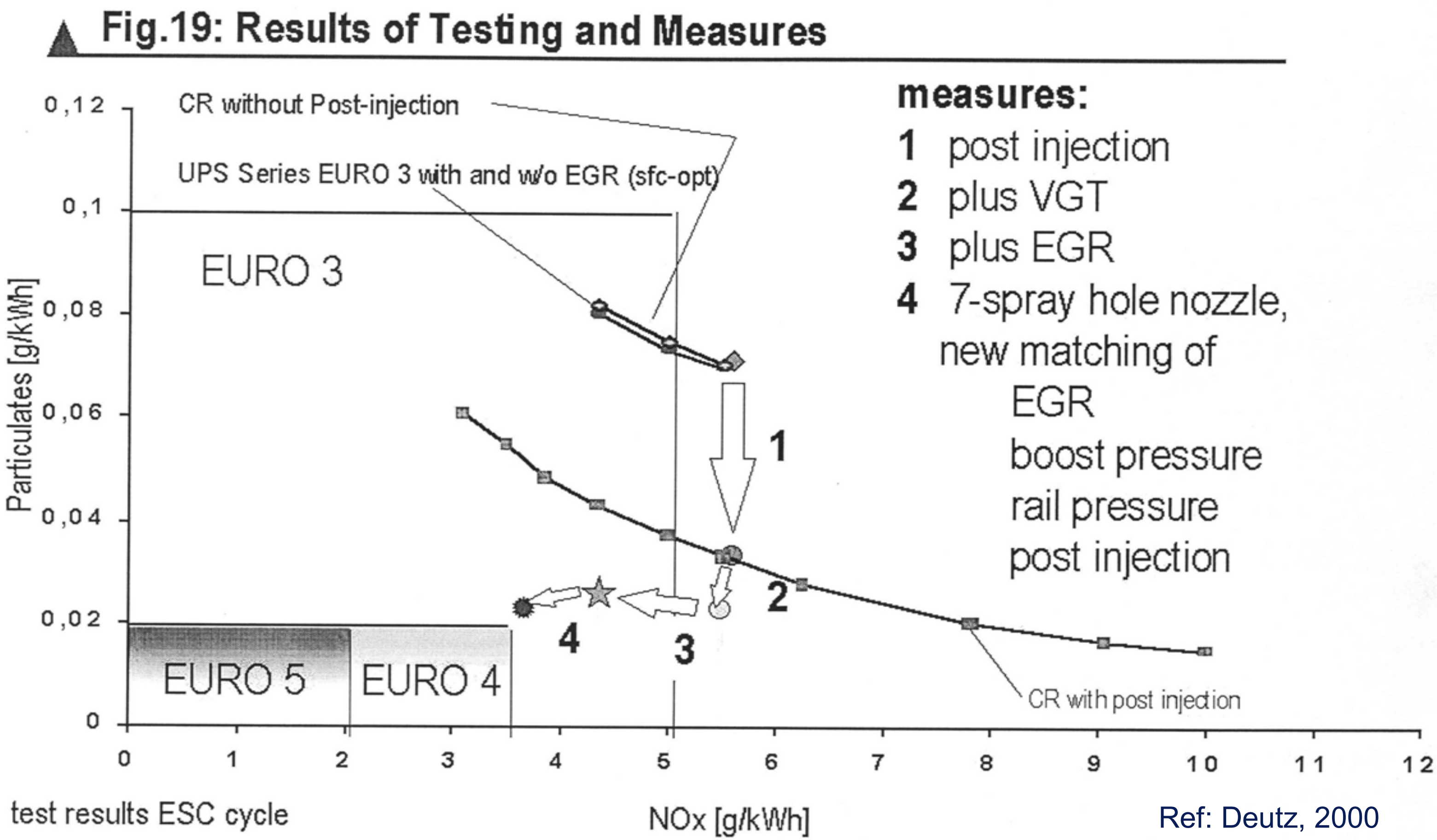




- Common rail has a pump driven via a belt or similar means from the crankshaft, which pressurises a rail to the pressure required by the ECU. Injection controlled via solenoid by the ECU to enable precise control.
- Electronic Unit Injectors are powered from a camshaft, which compresses the fuel. The injector is then opened in a similar way to the common rail injector

Effects of Post Injection (Common Rail)

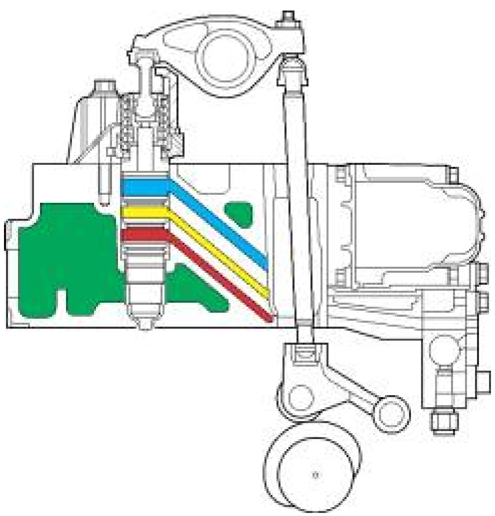
- The effects of multiple injection have been demonstrated on-highway by others e.g. Deutz in 2000

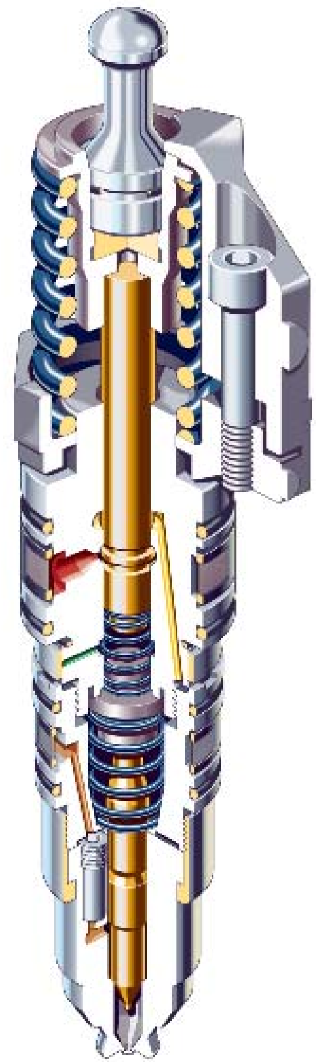


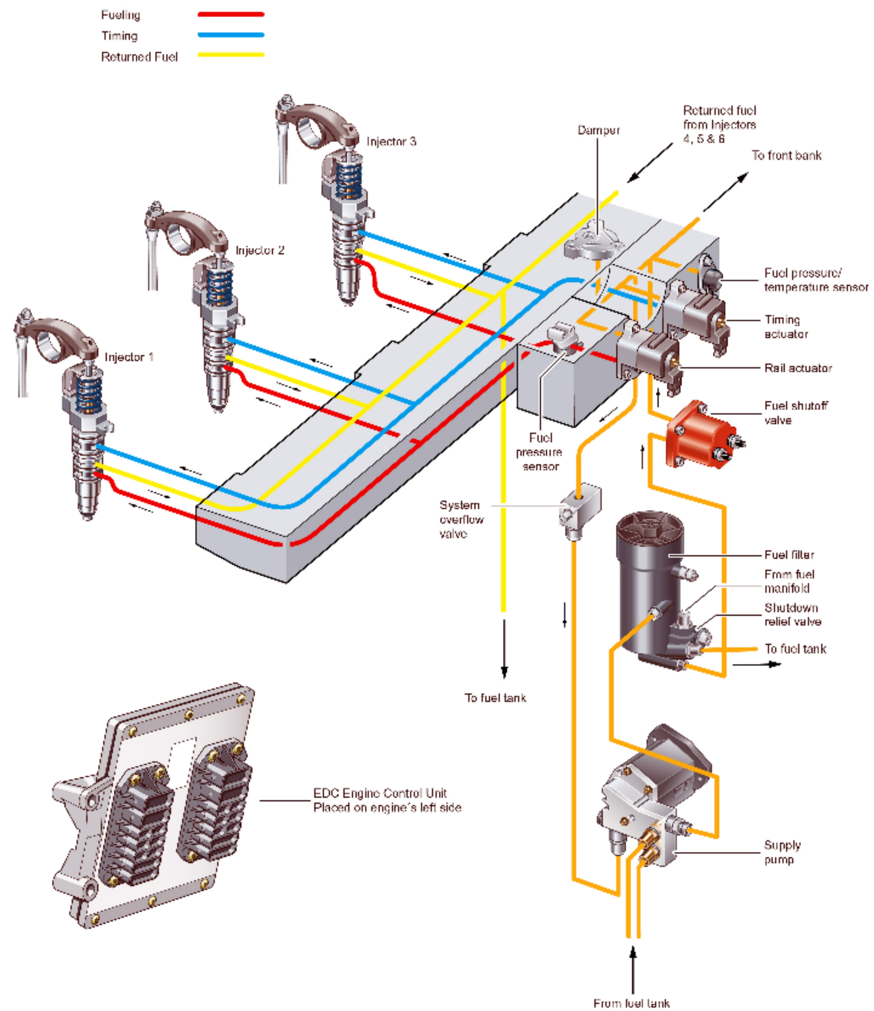
Ref: Deutz, 2000

Scania HPI Fuel Injection System

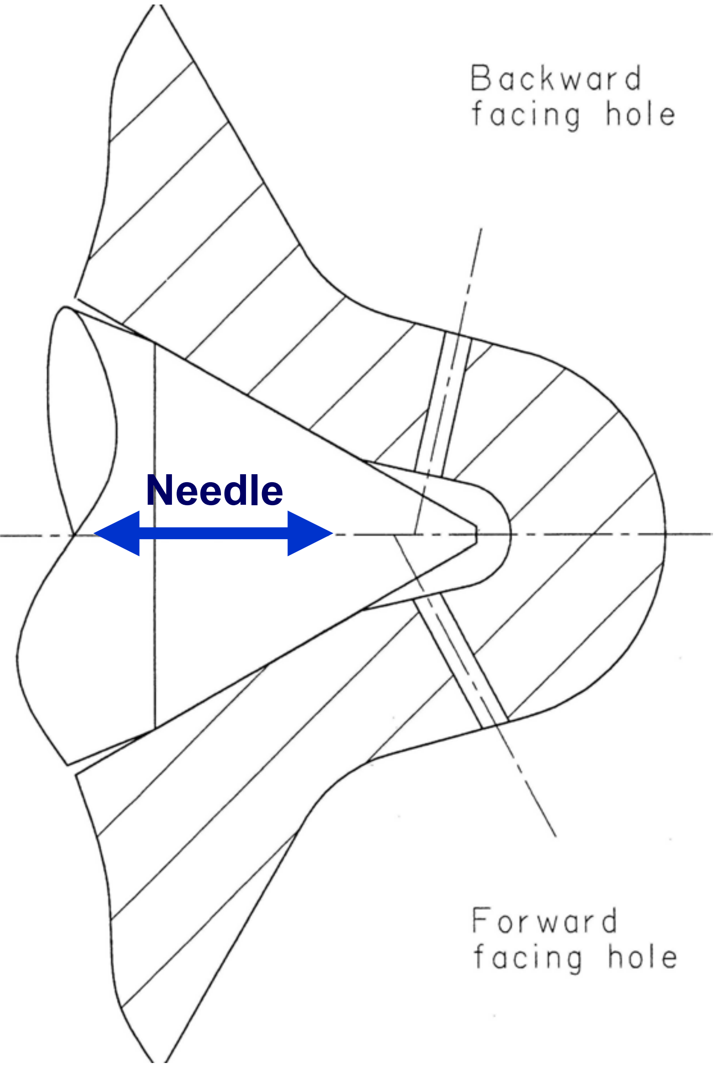
- Electronic version of Cummins PT system
- One stream of fuel used to displace piston for timing, the other for injected fuel



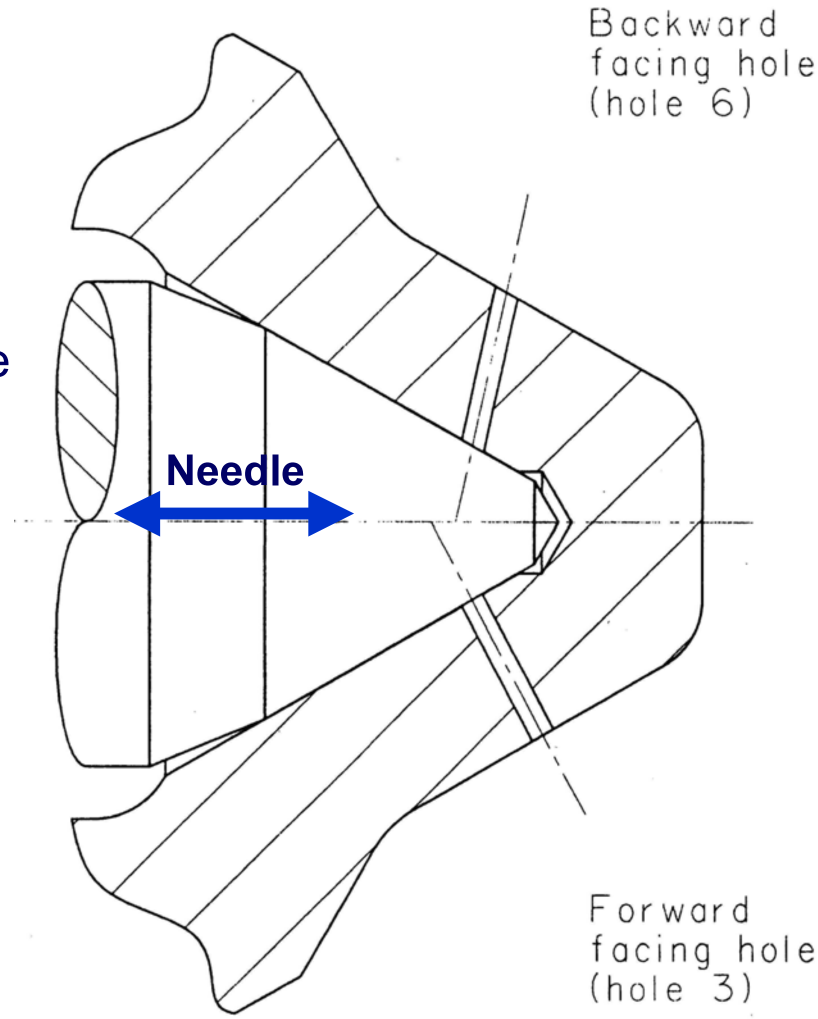




Fuel Injection Systems: DI Nozzle Types

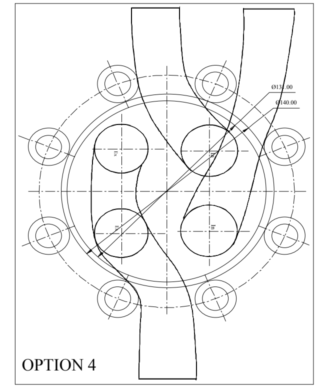


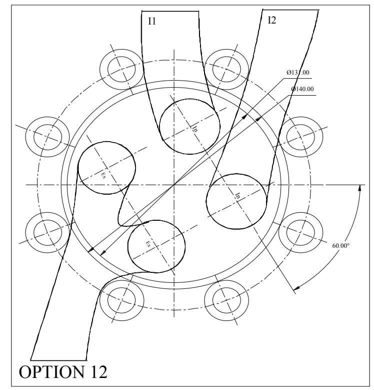
- Sac nozzle (left) allows some HC formation due to leakage from the sac, but is cheaper than
- Valve Closing Orifice (VCO) nozzle (right)
- Offset injectors require offset holes; main reason for diesel engines using 4 valves per cylinder, so allowing the injector to be placed in the centre of the combustion chamber

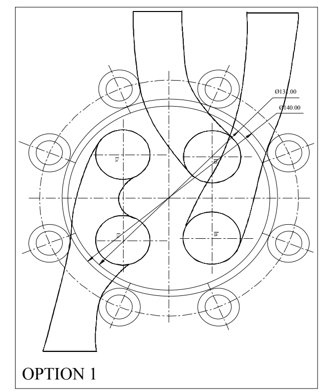


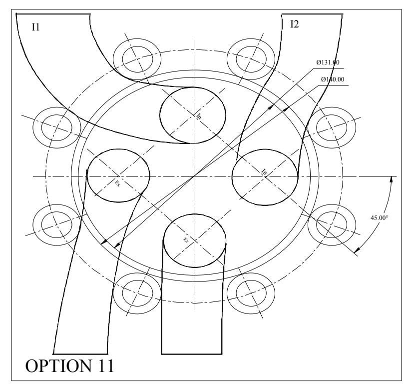
Engine Breathing

- Inlet porting affects degree of swirl in air motion, which in turn affects quality of combustion
- Engines went from 2 valves per cylinder to 4 in order to enable a central injector location
- This has in turn enabled significantly more even combustion, reducing PM emissions
- Advancing technology in the development arena has led to improvements in our ability to quickly optimise a design



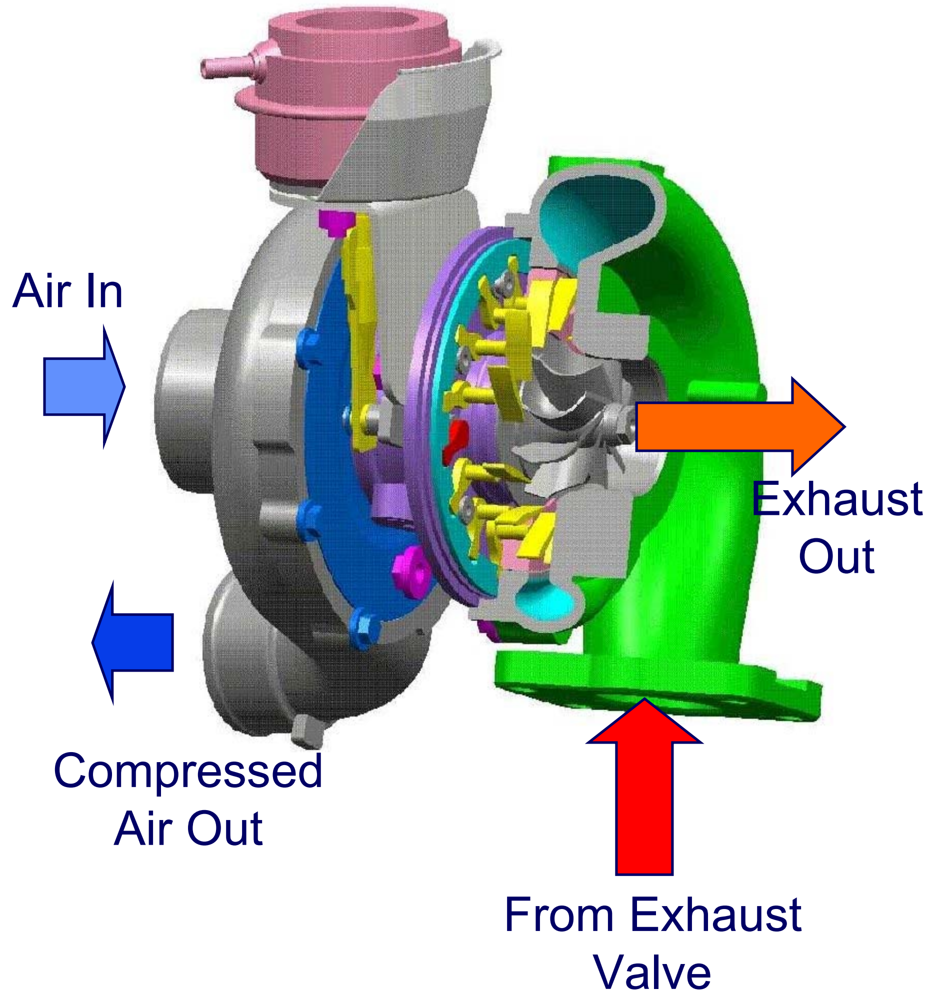






Engine Turbo-charging

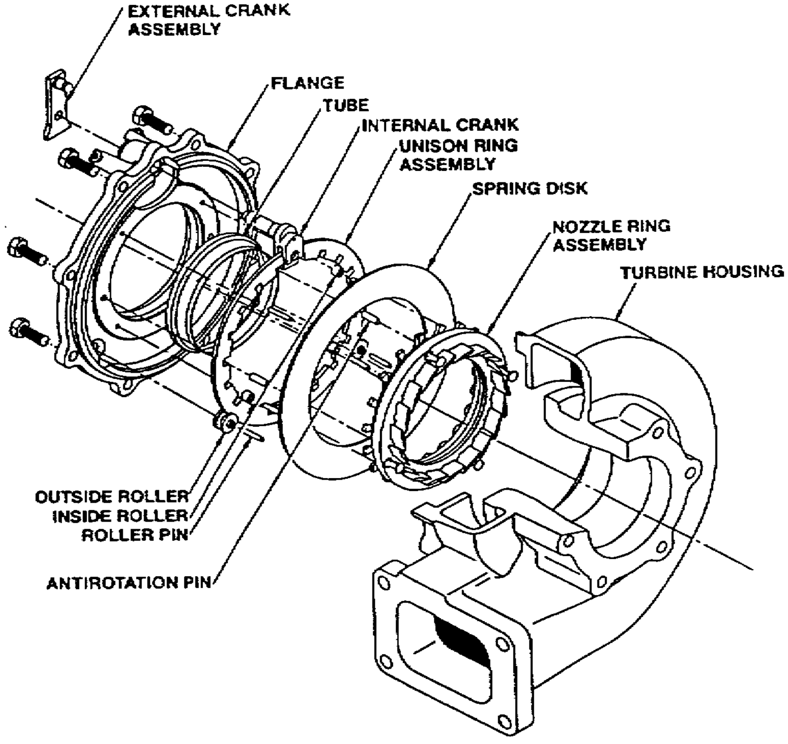
- Principal is the same for all engines:
  - Use the energy in the exhaust to drive a turbine,
  - Use the turbine to drive a compressor,
  - Use the compressor to compress air into the engine
  - Generate more power or replace power lost by reducing the engine displacement
  - After-cooling or "charge" cooling used to cool the compressed air before it enters the engine. This further increases engine performance



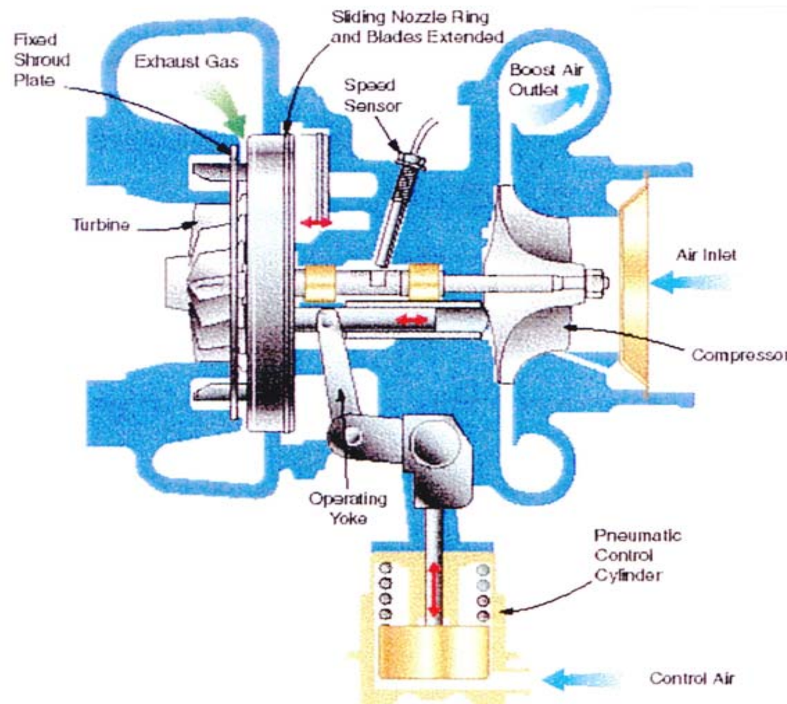
Boost Trends

- The advent of new HP FIE is enabling the use of higher levels of Exhaust Gas Recirculation (EGR) in the truck market, so the demand for higher boost levels has risen
  - Enable the level of EGR to be generated
  - Ensure target air/fuel ratios for low PM are maintained
- The typical truck application is configured with a boost pressure ratio of ~ 2.8:1 and a ceiling of 3.2 to 3.5:1 with today's turbomachinery
- Wastegate and variable geometry turbocharger technology is well established in both heavy duty truck and passenger car on-road markets
- Turbocharger manufacturers such as Holset have now introduced titanium rotor compressors in production to accommodate higher boost temperatures (>200°C) from the compressor
- Development units with 5:1 boost pressure ratio are now available but the size and price increase are both significant
- All this to enable better performance whilst maintaining low NOx and PM levels

Variable Geometry Turbines



Swinging Vane Type
(eg: Allied Signal on VW TDi)

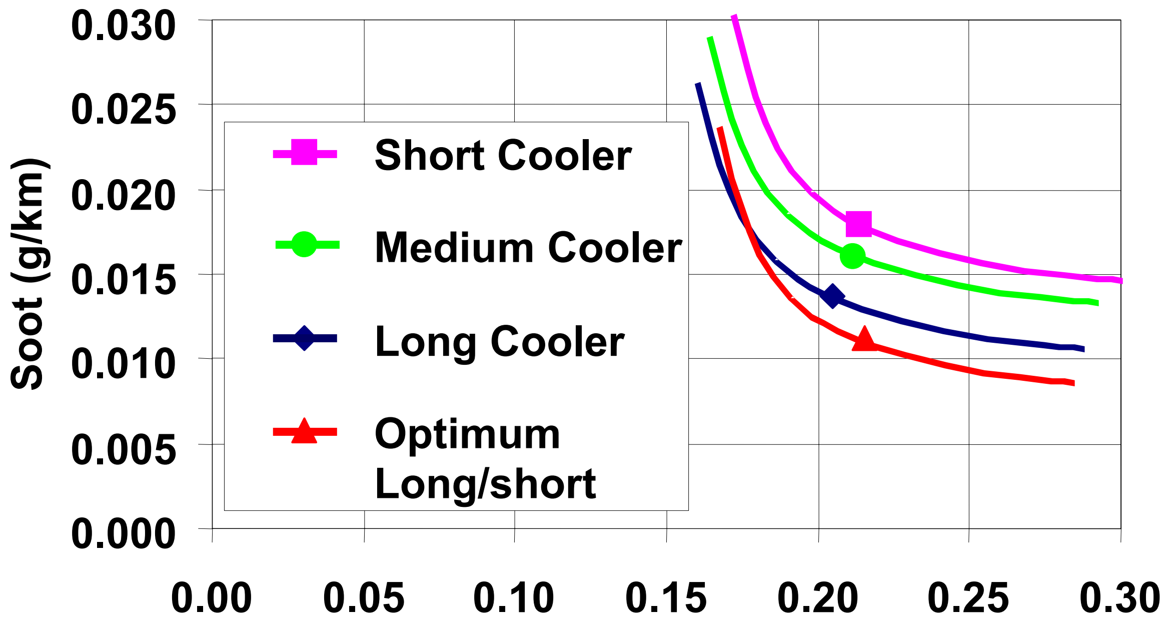


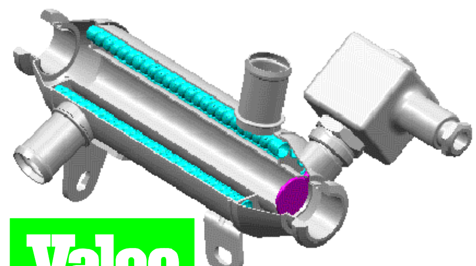
Moving Wall Type
(eg: Holset on Iveco Cursor)

- Can be used to increase efficiency or enable higher EGR levels to be attained at high loads, hence reducing NOx emissions

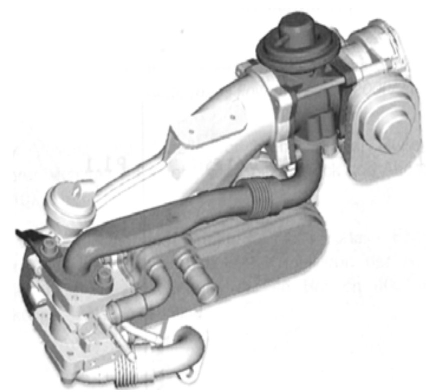
EGR Cooler With Bypass Temperature Control Improves Emissions

Predicted Engine Out NOx and Soot Emissions





Valeo ENGINE COOLING

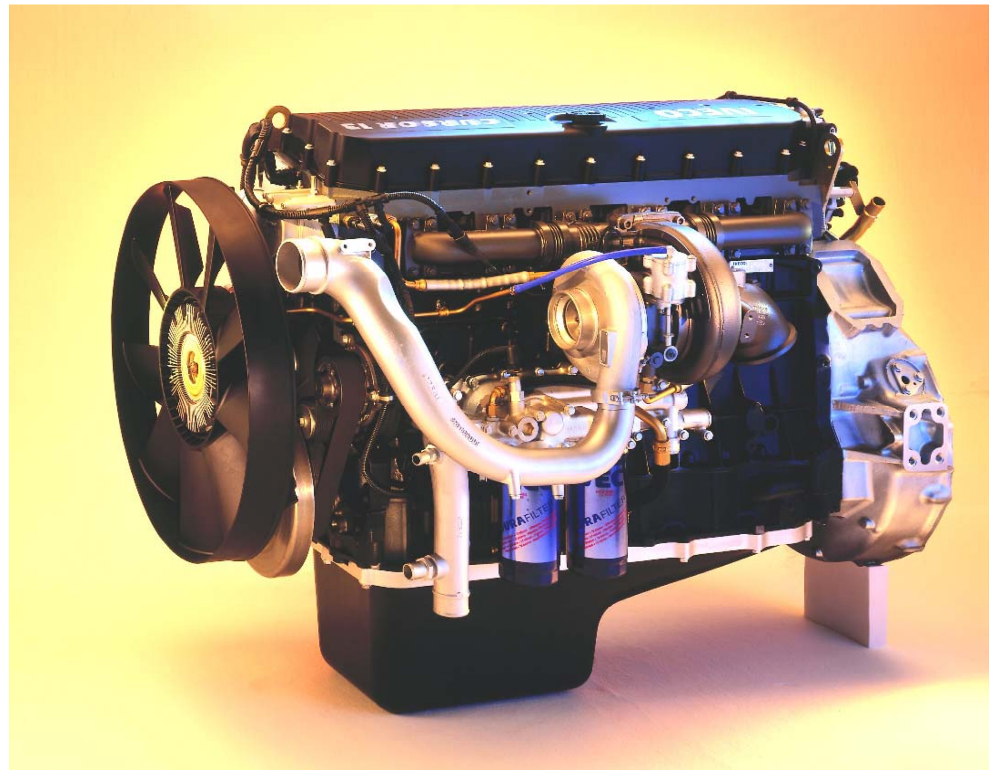


VW 1.9 TDI EGR cooler bypass

- Cooled EGR further reduces NOx by reducing gas temperatures throughout the cycle. However sizing the cooler is more complex that one might imagine
  - Variable EGR temperature control simulated by selecting best results
    - Short cooler results at low load (low CO, HC and soot)
    - Long cooler results at high load (improved NOx/soot)
  - Improved NOx and soot without compromising CO and HC compared to the medium cooler

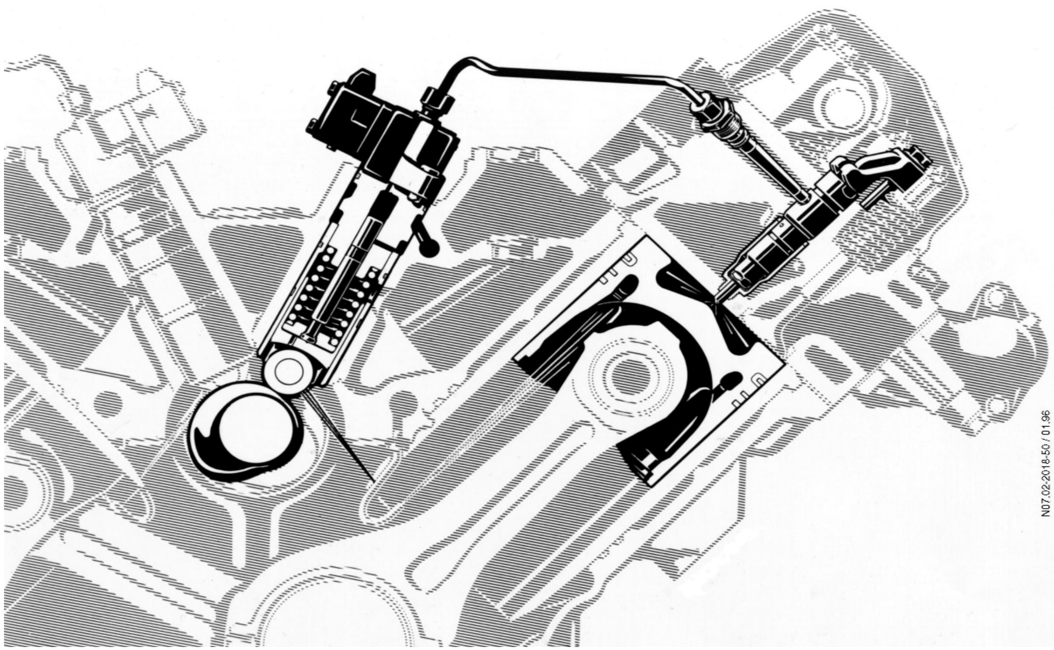
HDD Example: Iveco Cursor 13 litre

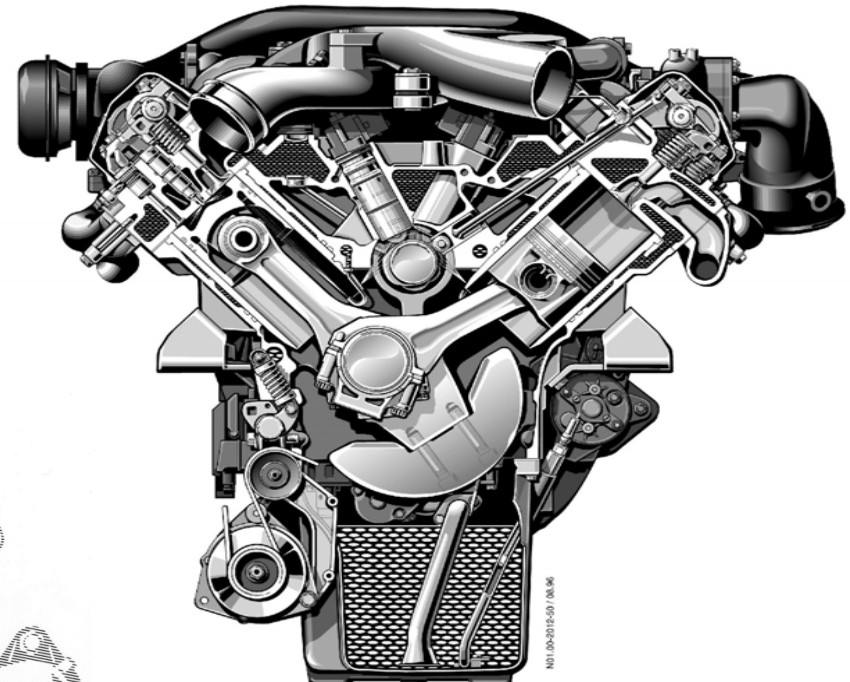
- 12.9 L In-line 6
  - addition to Cursor ‘family’ (7.8 L and 10.3 L)
- Holset moving-sidewall Variable Geometry Turbocharger
- Bosch Electronic Unit Injectors
- 4 valves/cylinder
- Overhead camshaft
- Cast in inlet manifold
- Gear drive at flywheel end
- Euro 3 328 kW @ 1900 rev/min (25.4kW/L)
- Euro 2 358 kW @ 1900 rev/min (27.8kW/L)
- 2140 Nm @ 1080-1550 rev/min (166 Nm/L)



Mercedes Benz OM502 LA

- The central cam, Direct Injection with Electronic Unit Pump and quill system which enables the engine width to be minimised



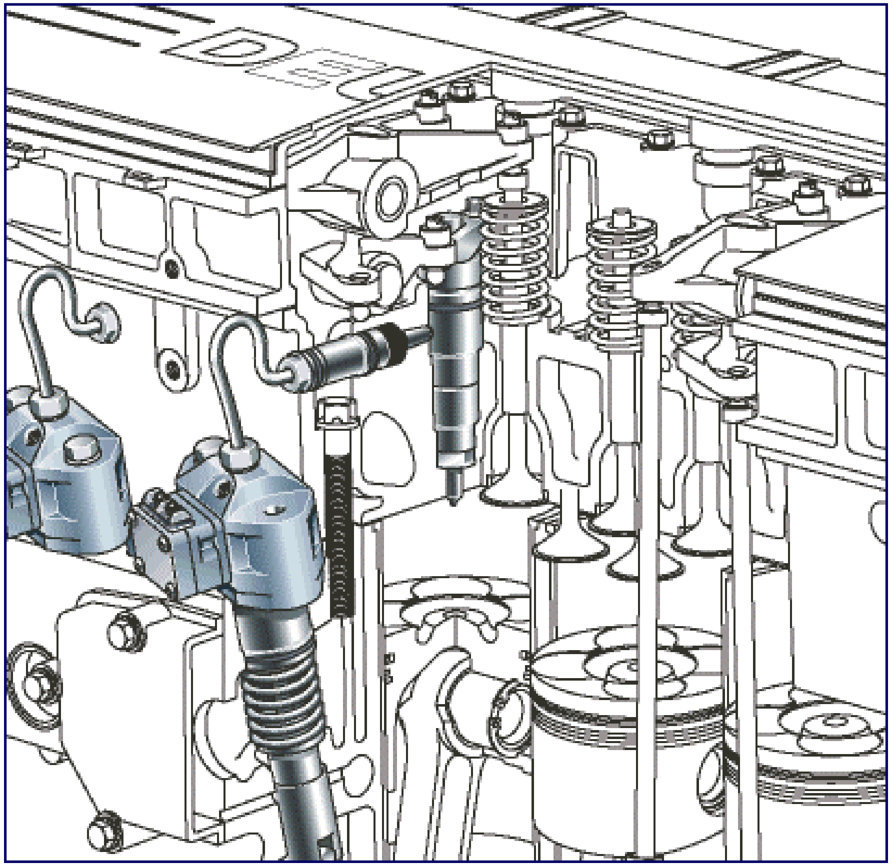


Motor OM 502 LA BM 542.920 (Querschnitt)

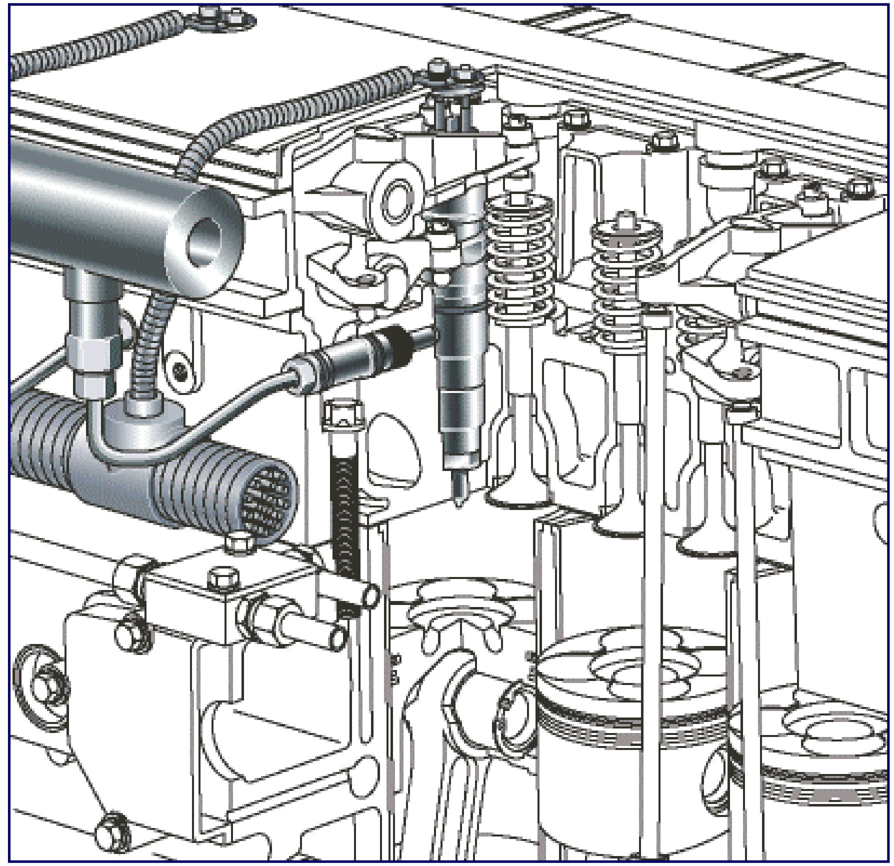
BF2013 with UPS / with CR system

Source Deutz Fisita 2002

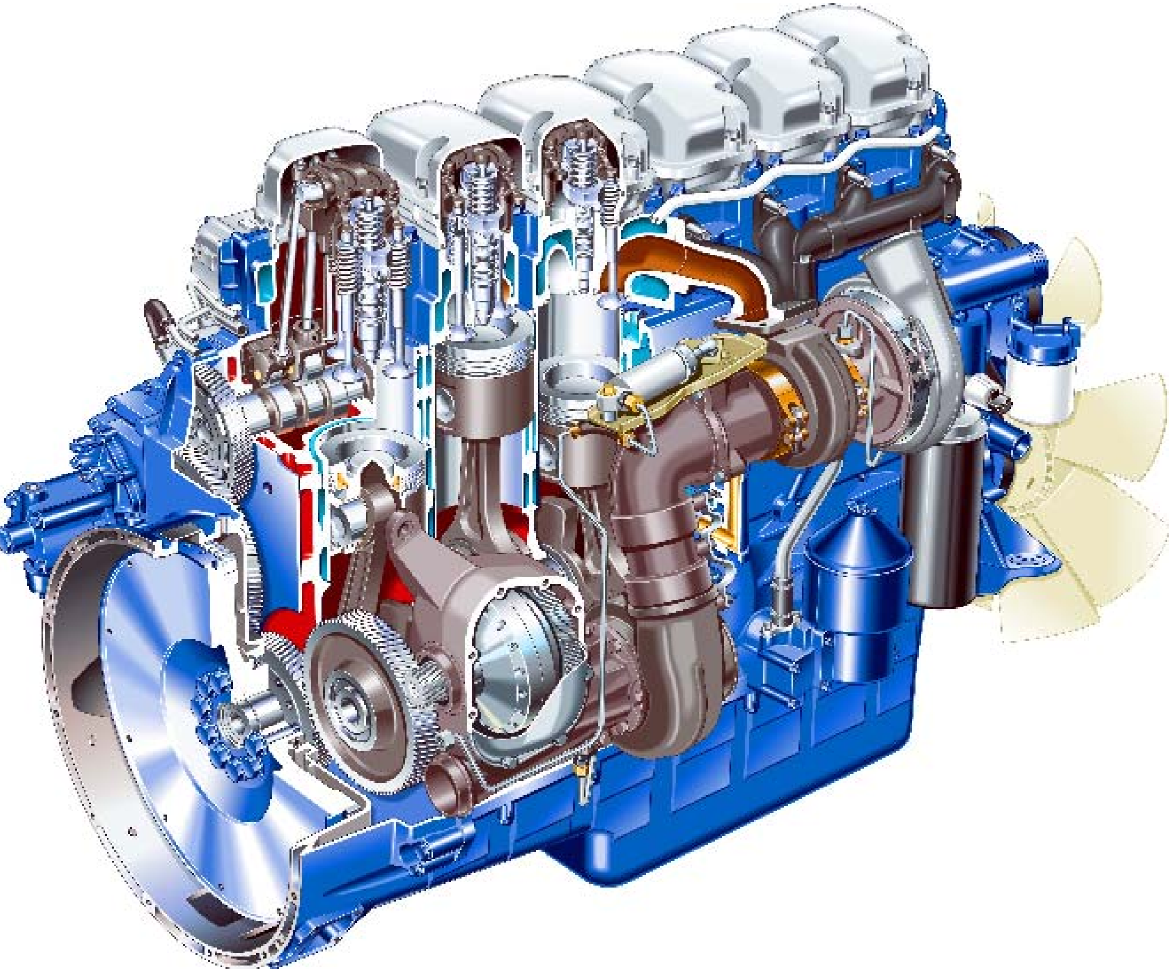
Unit Pump fuel injection (series, or production equipment)



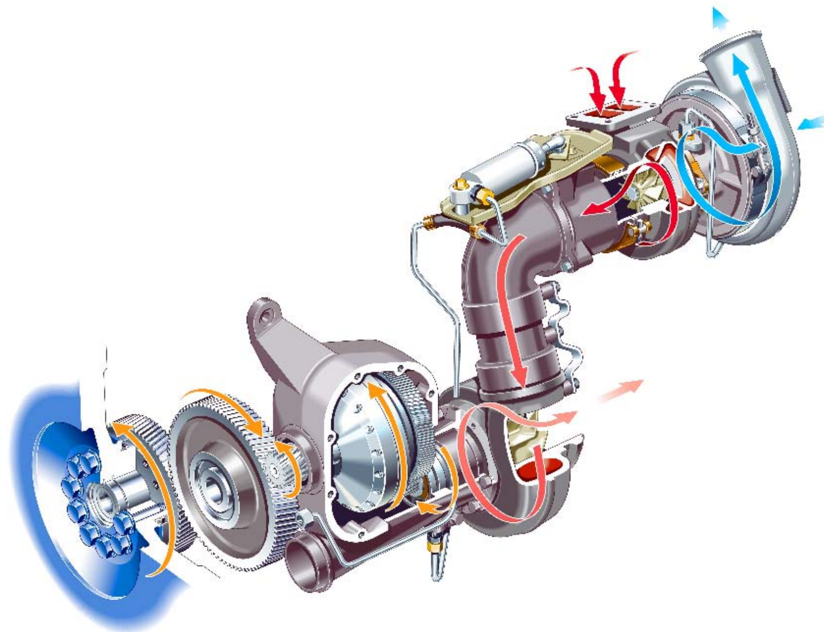
Common Rail system (prototype test engine)



Turbocompound Truck Engine Scania 470 Engine

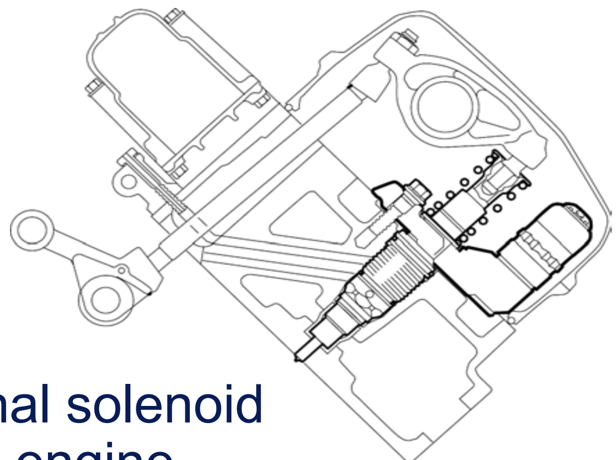


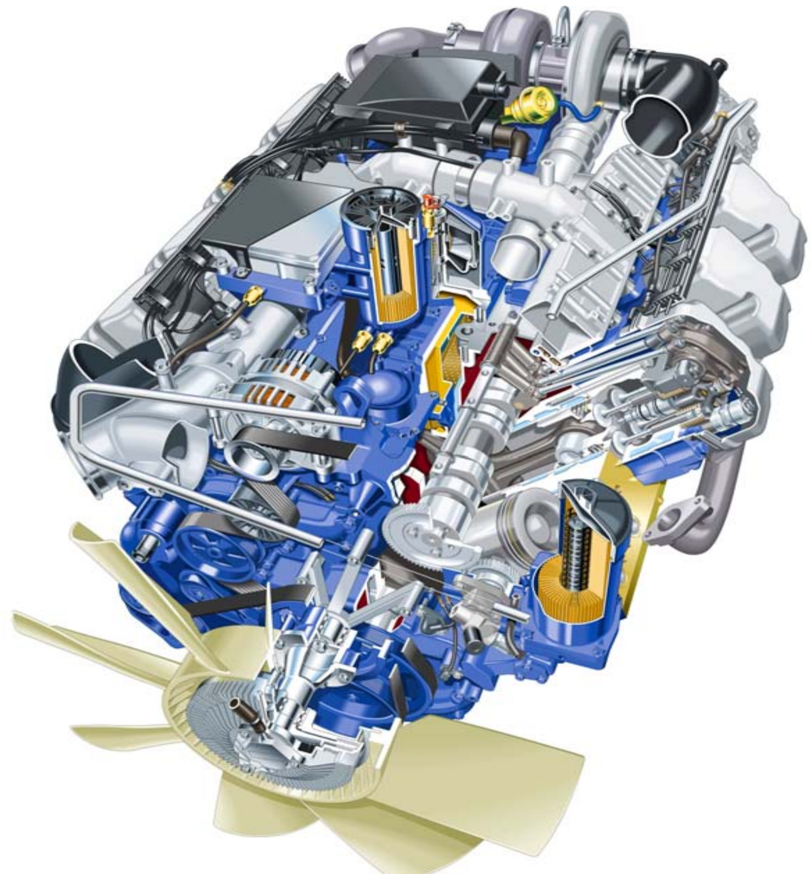
- Turbo compounding uses a second turbine in exhaust system recovers energy and feeds it back to the crankshaft via a gear train



Scania R164 with Bosch EUI

- 15.6 L V8
- Bosch Electronic Unit Injectors (EUI)
- 426 kW @ 1900 rev/min (27.3 kW/L)
- 2700 Nm @ 100-1200 rev/min (173 Nm/L)





- Conventional solenoid EUI makes engine wide
- Next generation EUI overcomes this problem

Key Aspects of Heavy Duty Diesel Engine Design – Euro 4

RICARDO

Euro IV	c.1.0 litre/cyl	c.2.0 litre/cyl
Chamber Layout		
Piston Bowl	Re-entrant	Open or slightly re-entrant
Cylinder Head Layout	3 or 4 valves/cyl	4 valves/cyl
Injection Location	Central, vertical	Central, vertical
Inlet Swirl Ratio	1.5~2.0 Rs (re-entrant bowl)	1.0~1.5 Rs (depends on bowl)
Compression Ratio	17.5:1~18.5:1	16.5:1 to 17.5:1
Boost Pressure Ratio	up to ~3.3:1	up to ~3.5:1
Aftercooler	Air-Air η~85%	Air-Air η~85%
Maximum BMEP (TCA)	21 bar	23 bar
Max. Cylinder Pressure	160~180 bar	180~200 bar
NOx Reduction	EGR or SCR	SCR or EGR
Fuel Injection System		
Type	Common Rail, Rotary Pump or EUI/EUP	EUI/EUP, Common Rail
Maximum Fuel Pressures	1600 bar (CR), 1900 bar (EUI/EUP)	1600 bar (CR), 2000 bar (EUI/EUP)

Key Aspects of Heavy Duty Diesel Engine Design – Euro 5

RICARDO

Euro V	c.1.0 litre/cyl	c.2.0 litre/cyl
Chamber Layout		
Piston Bowl	Re-entrant	Open or slightly re-entrant
Cylinder Head Layout	3 or 4 valves/cyl	4 valves/cyl
Injection Location	Central, vertical	Central, vertical
Inlet Swirl Ratio	1.5~2.0 Rs (re-entrant bowl)	0.5~1.5 Rs (depends on bowl)
Compression Ratio	17.5:1~18.5:1	16.5:1 to 17.5:1
Boost Pressure Ratio	up to ~3.6:1	up to ~4.0:1
Aftercooler	Air-Air η~85%	Air-Air η~85%
Maximum BMEP (TCA)	23 bar	25 bar
Max. Cylinder Pressure	170~190 bar	190~220 bar
NOx Reduction	SCR	SCR
Fuel Injection System		
Type	Common Rail, Rotary Pump or EUI/EUP	EUI/EUP (Smart injector), Common Rail
Maximum Fuel Pressures	1800 bar (CR), 2000 bar (EUI/EUP)	2000 bar (CR), 2200 bar (EUI/EUP)