Advanced Automotive Diesel Engines

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** Improvements in diesel engines can be achieved by combining a number of different technologies to improve efficiency and reduce emissions. These technologies include: **Piezo-injectors**; **Downsizing**; **Turbocharging**; **Cylinder deactivation**; **Optimised/advanced cooling circuit and electric water pump**; **Exhaust heat recovery**; and **Homogeneous charge compression ignition (HCCI)**.

■ **PERFORMANCE AND COSTS –** Implementing a full package of technologies would add (indicative only) incremental costs between €1135 for a small car and €1800 for a large car. It is estimated that these costs are likely to decline by around 10% in 2020 because of technology learning. The technologies covered - and related CO2 reduction and incremental compliance costs in 2008 Euros include: **a)** Reduced engine friction losses (3-5%, €40-60); **b)** Downsizing (3-10% €120-375); **c)** Exhaust heat recovery (1.5%, €45); **d)** HCCI (18-21%, €775-1,165); **e)** Optimised Cooling Circuit (1.5%, €35); **f)** Advanced Cooling Circuit and Electric Water Pump (3%, €120).

■ **POTENTIAL AND BARRIERS –** The increasing uptake of diesel vehicles is driven by further efficiency gains over gasoline and potential innovations that are not yet commercialised (e.g. HCCI). However, developments in advanced gasoline technologies are also likely to erode the performance gap with diesel and brake further expansion of the diesel market. In addition, the supply of diesel fuel is also constrained in some markets. Europe is already a net importer of diesel (and an exporter of gasoline to the US). While there are no general bottlenecks affecting the technologies described below, several of them still have a long way to go before they become commercial. Alternative technology options, increasing oil prices, incremental costs, as well as specific regional barriers, could slow down the deployment of diesel engines.

TECHNOLOGY STATUS AND PERFORMANCE – In general, advanced diesel engines gain efficiency through high compression ratios and reduced throttling or pumping losses. They may be turbocharged to recover exhaust heat and require a high-pressure fuel injection system to enable low-emission combustion. In addition, diesel engines have more advantages in torque over gasoline engines. With optimized transmission, this enables efficiency gains and the transmission to operate in higher gears for a longer period over the same drive cycle. The technologies listed in Table 1 can make contributions to better fuel economy and lower emissions. Rather than being radical innovations, many of these technologies have been in existence for several years and are advanced, refined and adjusted to optimise diesel technologies through e.g. re-engineering of associated systems, improved vehicle computer control and software sophistication, or changes in assembly procedures and systems. [1]

■ ***Piezo Injectors –*** Piezo-injectors are part of the improved fuel injection systems that allow much finer control and metering of the fuel spray while lowering consumption and emissions levels. Earlier injectors used electro-magnetic solenoids to move the injector needles and to allow the fuel to flow into the combustion chamber. Piezo-injectors use a stack of piezo-crystal plates that expand when an electric current is applied, which causes the needle to move. The expansion of the piezo-crystals is more precise and can be repeated more than the electro-magnetic solenoids, thus enabling precise fuel metering, lower consumption and emissions. In recent years a new generation of piezo-electric fuel injectors has been developed by companies like Bosch, Continental and Delphi. These are now heading towards commercial production. [2,5,8]

Table 1 - Advanced Diesel Technologies

Technology	Status
Piezo-injectors	Production
Downsizing	Production
Turbocharging	Production
Cylinder deactivation	Production
Optimised/adv. cooling and electric water pump	Production
Exhaust heat recovery	Prototype
Homogeneous charge compression ignition (HCCI)	Prototype

■ ***Downsizing –*** Downsizing forces the engine into higher load operation with better mechanical efficiency and reduced pumping losses. This permits the engine's power and torque to increase (thus responding to new market demand or compensating for increased vehicle weight) without increasing cylinder capacity. As an alternative, engine capacity may be reduced while producing the same power. Reducing engine capacity with same power permits reducing fuel consumption thanks to four basic factors: a) Reduced pumping losses (i.e. less volume is swept on each engine revolution, higher average load on driving cycle, higher

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average intake pressure); b) Reduced gas-to-wall heat transfer (i.e. reduced internal surface area as well as shorter flame travel distance and faster combustion resulting in reduced gases-wall heat exchange duration); and c) Reduced friction losses and smaller moving parts; d) Reduced engine weight and volume. The technologies available vary considerably as do their costs and associated CO_2 emission reductions (see Tables 3 and 4). While these technologies are already available on the market, they still have considerable innovation potential in the short to medium term. [1]

■ ***Turbocharging –*** Novel turbocharging systems allow downsized diesel engines to provide improved fuel efficiency and a similar (or better) performance than conventional larger engines. A good example is the twin sequential turbocharging system that is being used by major car manufacturers. It consists of two differently sized turbochargers operating at different engine speeds. They enhance fuel efficiency, and improve the generation of lean fuel/air mixtures in the engine, as well as the vehicle drivability. [1,8]. Manufacturers are starting to deploy the novel turbocharging systems.

■ ***Cylinder deactivation –*** By deactivating half of the cylinders, the remaining active cylinders operate at twice the load that the engine would normally operate at if all cylinders were active. This reduces the pumping losses and improves fuel consumption. Engines with cylinder deactivation can be found in several vehicles under various trade names such as Multiple Displacement System (MDS) and Active Fuel Management (AFM). To date, cylinder deactivation has been applied to V6, V8, and V12 engines. Mitsubishi applies cylinder deactivation to a 4-cylinder engine (MIVEC system), while Mercedes applies the technology to its V8 and V12 engines. New variable valve actuation (VVA) systems can facilitate cylinder deactivation.

■ ***Optimised/advanced cooling and electric water pump –*** These technologies account for coolant and oil thermal inertias to help reduce fuel consumption. During engine operation, the centre housing is integrated into the cooling loop of the engine. After the engine's shutdown, the residual heat is carried away by means of a small cooling circuit, which is driven by a thermostatically controlled electric water pump.

■ ***Exhaust heat recovery –*** Heat recovery from exhaust gas of the internal combustion engines has been deployed in the recent past. The recovered heat is used for such things as warming the engine, thereby improving the efficiency. Warming up the engine reduces friction loss and fuel need for cold-starting. Technologies include mechanical, electrical turbocompounding and Rankine Bottoming Cycles, as well as heavy vehicles technologies. [2, 9]

■ ***Homogeneous charge compression ignition (HCCI) –*** In the HCCI systems (Fig.1), the fuel-air mixture is ignited simultaneously throughout the entire volume of the cylinder, rather than being centralized at the fuel injector. HCCI combustion occurs much faster than conventional combustion. This leads to significantly higher peak pressure and a relatively lower peak temperature inside the combustion chamber. The lower temperature reduces NOx emissions, and the higher peak pressure allows a leaner fuel-air mixture (less fuel) to be used to obtain higher efficiency. As a consequence, emissions of CO_2 can be reduced by 18-21% while CO and various unburned hydrocarbons are produced in amounts comparable to a conventional gasoline vehicle and may be considerably reduced using ordinary exhaust treatment methods. Currently, no HCCI engines are being produced commercially. A number of motor manufacturers, including General Motors, Volkswagen, Honda, and Mercedes-Benz are all believed to have fully operating prototypes. While some estimate that this technology is close to commercial application it may not be until about 2015 before it is commercially available. [2, 7]

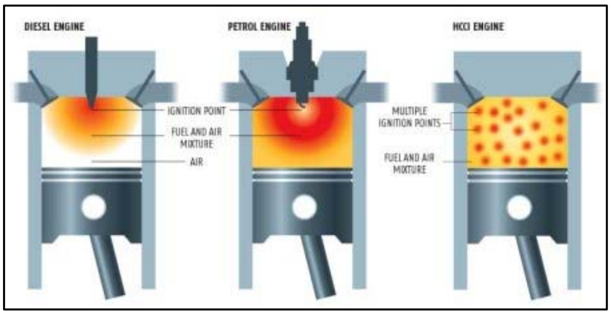

Fig. 1 - Diesel, Petrol and HCCI Engine

■ ***Reduced engine friction losses –*** Various technologies are aimed at reducing engine friction losses. They include the use of advanced components (ceramics, rollers) and lubricants, as well as reduced/enhanced throttling (electronic throttle control) and load control by valve timing.

Improvement in CO2 emissions obtained from all the technologies described above is estimated to range from 106.8 g/km to 159.5 g/km, depending on the size of the car. A recent test drive of a Vauxhall Vectra 2.2 HCCI engine resulted in the fuel efficiency increasing from 37 miles per gallon (mpg) to 43 mpg, an improvement of approximately 15%. A small advanced diesel vehicle is assumed to consume some 0.036 litre/km vs. 0.054 litre/km for large cars. [11]

CURRENT COSTS AND PROJECTIONS – A package of advanced diesel technologies could perhaps include an advanced cooling circuit and electric water pump, optimised cooling circuit, HCCI, exhaust heat recovery, downsizing and reduced engine friction. This package would add incremental costs to new

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vehicles ranging from €876 for a small car to € 1318 for a large car. It is estimated that these costs are likely to decline by around 10% in 2020. [3, 10, 11].

Technology developments and further refinement in the materials will deliver improved performance while costs and further governmental regulations will help to reduce emissions. It is also important to consider regional differences. The increase of advanced diesel vehicles in Europe (Fig. 2) is due to two main factors. First, diesel offers increased fuel economy vs. gasoline vehicles, with little or no compromise in performance (in modern vehicles). Second, market-based incentives - linked to Euro IV and V emissions standards implementation - may result in an increasing drive towards biasing vehicle taxation and variable urban congestion "fees" against CO_2 emissions. Additional drivers are the European industry voluntary agreements [14], now superseded by mandatory fleet average improvements in a recent EC Directive. [3,10,11,16]. In the US, CAFE standards have been tightened, most notably in California where state-owned CO_2 standards have now been enacted. [13]

POTENTIAL AND BARRIERS – In spite of specific technical bottlenecks, advanced diesel technologies offer better fuel economy over conventional gasoline technology under all driving conditions, and with no detriment to performance. Besides fuel economy and lower CO_2 emissions, diesel engine advantages include improved performance and towing, and high torque at low engine speed giving "fun-to-drive" characteristics. In the next 20 years, technology innovations such as HCCI are expected to play a role in the uptake of diesel vehicles internationally. Diesel engines should be promoted particularly for use in heavy duty vehicles. However, competing developments of advanced gasoline technologies are likely to erode diesel advantages. Possible constraints in regional diesel fuel supply may also brake further expansion of the diesel market. There is indeed a limit as to how far the refinery fraction for diesel can be pushed [4, 6, 12]. Europe is already a net importer of diesel (and a gasoline exporter to the US). From a technical point of view, some advanced diesel technologies still have a long way to go until they are on the market. [17, 18, 19] For example, cylinder deactivation and HCCI have two important restrictions to be resolved. The integration of **cylinder deactivation** into the vehicle is challenging as active engine mounts are needed to run deactivated at idle. Noise quality from both intake and exhaust is problematic. Deactivation is typically used in the highest two gears only. In many cases, it is difficult to maintain the vehicle in deactivated mode at around 70 mph, which can lead to customer dissatisfaction with fuel consumption. However, as the vehicle specific power rating improves, the potential fuel consumption benefit increases. Similarly, during **HCCI** operation, engine control is very difficult as the ignition timing is not directly under control.

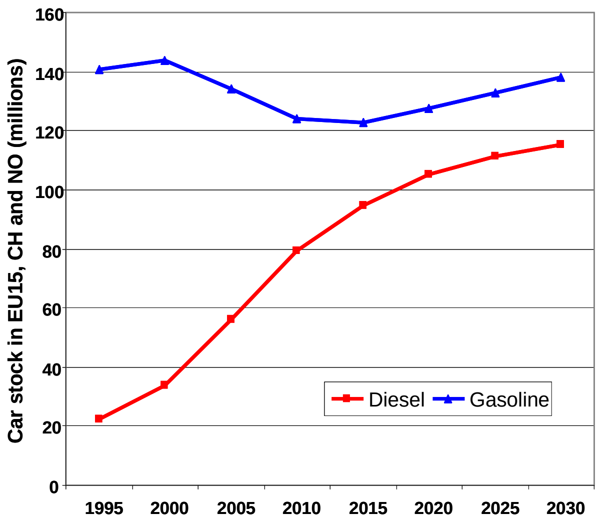

Fig. 2 - Diesel vs. Gasoline car stock in EU15, Switzerland and Norway. (Tremove[1] v2.7b Basecase Pivots)

This is different to conventional gasoline or diesel engines where the ignition is controlled directly by sparks or injectors. In order to maintain good operation in HCCI mode, very fast and precise control is required, making advanced engine control units, sensors and actuators necessary. As a consequence, further development is needed to

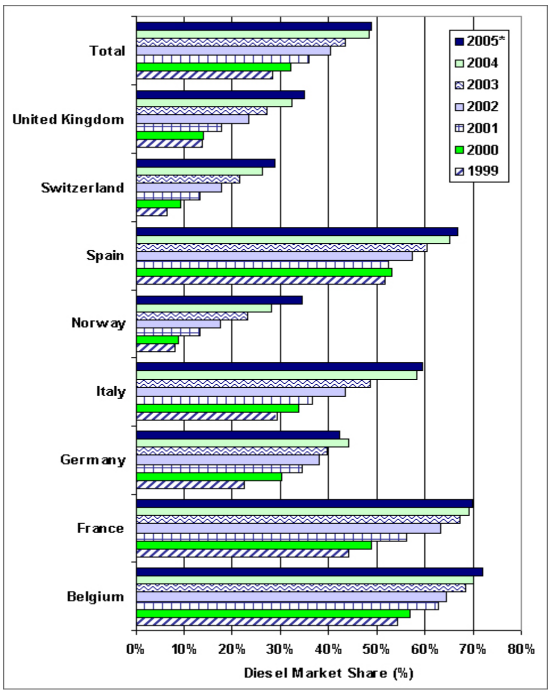

Fig. 3 - US DoE – Vehicles Technology Programs (http://www1.eere.energy.gov/vehiclesandfuels/facts/2005/m/fcvt_fotw386.html)

[1] http://www.tremove.org/documentation/index.htm

ensure robust operation of HCCI in all conditions before it becomes available to consumers. [7, 15, 16] Other barriers may slow down the development and deployment of advanced diesel technologies. For instance, manufacturers may choose to focus on alternative new technologies such as hybrid technologies, plug-in electric vehicles or fuel cell cars, or increasing oil prices as well as significant incremental investment cost of diesel vehicles, may lead consumers to different choices. There are also regional barriers. For example, the US requires significantly lower NOx emissions than Europe. This is a challenge for lean combustion technologies such as diesel engines. The US emissions levels can be achieved but require significantly more complexity in the after-treatment systems and novel air and exhaust flow management.

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Table 2 - Summary Table: Key Data and Figures for Baseline and Advanced Diesel Vehicles - Source [9, 20]

Baseline Diesel Vehicles*			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Diesel		
Energy Output	Kilometres		
Base Energy Consumption, l/km	0.049	0.057	0.075
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO2 and other GHG emissions, g/km	130.2	152.2	201.9
Costs			
Capital Cost, overnight, Euro/unit	10,691	17,497	26,160
O&M cost (fixed and variable), Euro/km	0.03	0.04	0.05
Economic Lifetime, yrs	12	12	12

Advanced Diesel Vehicles			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Diesel		
Energy Output	Kilometres		
Base Energy Consumption (l/km)	0.045	0.052	0.070
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO2 and other GHG emissions, g/km	106.8	123.3	159.5
Costs			
Additional Capital Cost, overnight, Euro/unit	876 –1,108	1,319 – 1,319	1,119 – 1,318
O&M cost (fixed and variable), Euro/km	0.04	0.04	0.05
Economic Lifetime, yrs	12	12	12

Table 3 - CO_2 reduction potential of Advanced Diesel Technologies

CO2 reduction (%)	TNO 2006			CCC (2008)		
	Small	Medium	Large	Small	Medium	Large
Reduced engine firction losses	3	4	5			
Mild, medium or strong downsizing	3 - 5	3 - 7	3 - 10			
Exhaust heat recovery		1.5	1.5			
Homogeneous charge compression ignition				18	19	21
Optimised Cooling Circuit	1.5	1.5	1.5			
Advanced Cooling Circuit and Electric Water Pump	3	3	3			

Table 4 - Incremental Costs for Advanced Diesel Technologies

Additional costs (Euro)	TNO 2006 [10]			CCC (2008)		
	Small	Medium	Large	Small	Medium	Large
Reduced engine friction losses	40	50	60			
Downsizing	120-160	150-300	180-375			
Piezo injectors						
Cylinder deactivation						
Exhaust heat recovery		45	45			
Homogeneous charge compression ignition				775 - 955	1137	965 -1165
Optimised Cooling Circuit	35	35	35			
Adv. Cooling Circuit and Electric Water Pump	120	120	120			

*The baseline diesel vehicles are assumed to be equipped with: a 4-cylinder in-line engine, common direct injection, 5-speed manual. The data were used as input for the construction of cost curves and the assessment of the overall costs and CO2-abatement costs of reaching the 2008/9 target of 140 g/km and various targets between 140 and 120 g/km in 2012

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