Advanced Automotive Gasoline Engines

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** Internal combustion engine technology is constantly evolving. A number of improvements in gasoline-powered vehicles have been made to optimize combustion, improve fuel economy and reduce emissions. Examples of advanced gasoline technologies include **reduced engine friction losses**, **direct gasoline injection**, **engine downsizing with turbocharger**, **variable valve actuation** (VVA) and **homogeneous charge compression ignition** (HCCI). The majority of these technologies are already commercially available or close to being on the market. Although HCCI technology is still under development for both gasoline and diesel engines, it promises improvement in fuel economy and exceptionally low NO_x and soot emissions.

■ **PERFORMANCE AND COSTS –** A study by the US Environmental Protection Agency (EPA, 2008) presents the potential CO_2 reduction and incremental compliance costs for a number of advanced gasoline technologies as compared to conventional port-fuelled injection vehicles. The costs account for both direct manufacturing costs and indirect costs. The technologies covered - and related CO_2 reduction and incremental compliance costs in 2006 US dollars – include a) engine friction reduction (1-3%, $0-126); b) homogeneous direct injection (1-2% $122-525); c) stratified direct injection (9-14%, $872-1275); d) downsizing with turbocharging (6-9%, $120-690); e) variable valve timing (1-4%, $59-209); f) variable valve control (3-6%, $169-1262); and g) cylinder deactivation (6%, $203).

■ **POTENTIAL AND BARRIERS –** Car ownership is expected to grow in many OECD countries as well as in emerging economies. Demanding environmental concerns and fuel economy standards, as well as increasing fuel prices, are the major drivers for advancement in engine technologies. The IEA study *Energy Technology Perspectives* (IEA, 2008) suggests that improving the fuel economy of light-duty vehicles (car, small van and sport utility vehicles) would be one of the most important and cost-effective measures to help reduce CO_2 emissions in the transport sector. Given the maturity of some advanced gasoline technologies, and the near-term and cost-effective solutions they can offer to energy and emissions concerns, there is neither technical-economic nor infrastructure barrier for deployment, although some technical bottlenecks have to be solved for technologies such as the HCCI.

TECHNOLOGY STATUS AND PERFORMANCE - Advanced gasoline technologies include a variety of new components and systems aimed at optimizing combustion and thereby improving the fuel economy and reducing the emissions of greenhouse gases and other pollutants. Major innovations are listed in Table 1.

Table 1 – Advanced Technologies for Gasoline Engines	
Technology	**Status**
Reduced Engine Friction Losses	Production
Direct Gasoline Injection (incl. homogeneous/ stratified charge)	Production
Downsizing with Turbocharging	Production
Variable Valve Actuation	Production
Cylinder Deactivation	Production
Variable Compression Ratio	Prototype
Homogeneous charge compression ignition (HCCI)	Prototype

■ ***Reduced engine friction*** technologies include systems, components and materials that minimize the friction between moving metal parts in the engine. These technologies are available in a significant number of engine designs [1]. Several friction reduction opportunities have been identified in piston surfaces and rings, crankshaft design, improved material coatings and roller cam followers. Various studies suggest that the CO_2 reduction potential for engine friction reduction technologies may range from 1-5% [1,2,3].

■ In the ***gasoline direct injection (DI) engines,*** fuel is injected at high pressure directly into the combustion chamber rather than into air intake manifolds. The key advantage is the improvement in fuel efficiency. The technology was developed more than 10 years ago and a number of different manufacturers are now using these types of engines in commercially available vehicles. The use of sulphur-free fuels is necessary to obtain the maximum benefit from this technology. Depending on the ignition and combustion mode and on the formation process of the mixture, DI engines can be categorized in *homogeneous charge*, and *stratified charge*, spark ignition. In the ***homogeneous charge (stoichiometric) DI engines***, a high-pressure fuel injector sprays fuel directly into the combustion chamber early enough in the cycle to promote homogeneous fuel-air mixing. These engines have the potential to reduce hydrocarbon emissions, increase power and improve fuel economy, while taking advantage of the highly-effective catalytic after-treatment systems, the same as the port fuel injection (PFI) engines. Various studies suggest a CO_2 emission reduction potential ranging from 1-5% [1,3,4] in comparison with PFI and multi-point injection. These engines are often supplemented with turbo-charging, supercharging[1], or both[2]. They are available from

[1] Turbochargers and superchargers are air compressors that allow more air into an engine; turbochargers are powered by exhaust gases, while superchargers run directly on engine power.

Please send comments to Tom.Palmer@aeat.co.uk, Nikolas.Hill@aeat.co.uk, Johannes.VonEinem@aeat.co.uk, Yvonne.Li@aeat.co.uk (Authors), and to Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org), Project Coordinators

several automobile companies worldwide, and more deployment is expected in the near future. ***Stratified charge DI engines*** involve concentrating fuel spraying close to the spark plug rather than throughout the whole of the combustion chamber. The aim is to produce an overall lean stratified mixture. These engines operate in at least two modes, depending on load and speed. During low-load and low-speed operation, the engine runs with a stratified charge and with lean mixtures. At high-load and high-speed operation, the engine operates as a stoichiometric homogeneous charge DI engine. These engines offer higher CO_2 reduction potential than homogenous charge DI engines, ranging from 8-14% compared to PFI and multi-point injection [1, 2 , 3, 4], However, major impediments are cost, complexity and the requirement of expensive lean NO_x traps in the exhaust after-treatment system. Stratified charge DI engines are currently in production *(wall-guided* variant*)*, but there is a shift towards the *spray-guided* injection variants [1, 4, 5] as they improve injection precision and targeting towards the spark plug, thus increasing lean combustion stability. These systems offer improved fuel economy and reduced emissions. Stratified charge *spray-guided* DI engines are nearing production[3]. The availability of low-sulphur fuels and improved lean catalyst technology will speed the process up.

■ ***Engine downsizing*** is seen as one of the most important technologies to reduce fuel consumption and CO_2 emissions through improved engine efficiency, lower weight and lower frictional losses [6,7]. It involves a substitution of a naturally-aspirated engine by an engine of smaller swept volume. The downsized engine is typically turbocharged to maintain adequate levels of torque and power output. The amount by which the engines are downsized vary depending on the amount of boost provided by the turbocharger and/or supercharger. For example, automotive brochures show that a 1.4 litre engine with the application of both turbo and supercharging provides an average fuel economy of 13.9 km/l in the combined cycle and produces torque (240 Nm) equivalent to a 2.5 litre standard gasoline engine (which has an average fuel economy of 10 km/l) [8, 24]. Another automotive brochure suggests that a 2.5-litre gasoline engine with the power of 123 kW and torque of 211 Nm can be replaced by a 2-litre turbo engine, with a 9% reduction in fuel consumption [9]. Depending on the amount of downsizing, various studies suggest a 2-12% CO_2 reduction.

■ ***Variable Valve Actuation (VVA)*** involves controlling the lift, duration and timing of the intake (or exhaust) valves for air flow. There are two main variants: ***variable valve timing (VVT)*** and ***variable valve lift systems (VVL)***. The **VVT** has now become a widely adopted technology. Manufacturers are using many different types of VVT mechanisms (or cam phaser systems) to control timing of the intake and exhaust valve. The advantages of using VVT include improvement in full-load volumetric efficiency which results in increased torque and reduction in pumping losses during low-load operation, which results in reduced fuel consumption. Depending on the design, EPA (2008) estimates that VVT may enable 1-4% reduction in CO_2 emissions compared to fixed-valve engines. The **VVL system** controls the lift height of the valves using two different approaches: discrete VVL and continuous VVL. Compared to VVT, VVL offers a further reduction in pumping losses and low-load fuel consumption. There may also be a small reduction in valve train friction when operating at low valve lift. Most of the fuel economy gain is achieved with VVL on the inlet valves only. This is considered to be a cost-effective technology when applied in addition to VVT (cam phase control) [1]. A number of manufacturers have implemented VVL (or VVT with VVL) into their fleet [10, 11, 12]. Based on standard (ECE) driving cycles, automotive brochures suggest that the VVL system provides fuel savings of up to 10%, and improves cold start behaviour [10]. Various studies confirm CO_2 reductions of 3-7%.

■ ***Cylinder deactivation*** allows an engine to run on part (usually half) of its cylinders during light-load operation. For example, a 6-cylinder (V6) engine will run on all cylinders during acceleration (or under high load), and switch to four or three cylinders for cruising or low-speed drive. This technology is aimed at large capacity engines (V6, V8 and V12 engines). Pumping losses are significantly reduced when the engine is operated in the “part-cylinder” mode. Several manufacturers have recently incorporated this application into their models. EPA (2008) and IEA (2005) suggest that CO_2 reductions associated to these systems range from 6-8%.

■ ***Variable Compression Ratio (VCR)*** technology enables the compression ratio of an engine to be automatically adjusted to optimise the efficiency of the combustion process under different load and speed conditions. The compression ratio controls the amount by which the fuel/air mixture is compressed in the cylinder before it is ignited. This is one of the most important factors that determines how efficiently the engine can utilize the fuel energy. At low speed, a VCR engine operates with high compression ratio in order to maximize fuel efficiency, whilst at high speed, low compression ratios are used. The potential benefits and the importance of VCR technology have long been known, but it is not commercially available yet due to its mechanical complexity. Research done by the European Commission Community showed that VCR engines can achieve a reduction of fuel consumption of up to 9%, compared to state-of-the-art turbocharged gasoline engines with a constant compression ratio of 8.9 [13]. It also suggests that an additional fuel savings of up to 18% can be obtained by downsizing the engine by 40%, while keeping torque and performance constant through high boosting. Thus, this technology could enable an overall fuel consumption reduction of up to 27%.

[2] US EPA (2008) suggests that a turbo and downsized stoichiometric GDI offers CO_2 reductions of 5-7% relative to stoichiometric GDI without boosting.
[3] According to Drake and Haworth (2007), SG-SIDI engines with piezoelectric pintle injectors are nearing projection.

Please send comments to Tom.Palmer@aeat.co.uk, Nikolas.Hill@aeat.co.uk, Johannes.VonEinem@aeat.co.uk, Yvonne.Li@aeat.co.uk (Authors), and to Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org), Project Coordinators

■ ***Gasoline Homogeneous Charge Compression (HCCI)*** - also known as Controlled Auto-ignition (CAI) - is an alternative engine-operating mode that does not rely on the spark events to initiate the combustion. In the HCCI engine, fuel and air are premixed to form a homogeneous mixture; on compression, combustion occurs by self-ignition at multiple sites [1, 5, 9]. HCCI operates in a very lean fuel-air mixture or with a mixture that is considerably diluted with exhaust gases either re-injected (EGR) or kept in chamber (to increase the charge temperature as well as to control excessive rates of heat release) [1, 4, 14]. A major advantage of HCCI is the exceptional low level of NOx emissions due to the lower peak-temperature inside the combustion chamber. High CO and unburned hydrocarbons emissions can be the result of incomplete reaction in cool wall boundary layers, but conventional three-way catalysts are most efficient for removal. Soot emissions are also very low or negligible due to the homogeneous nature of the premixed charge. In terms of fuel economy, the technology can lead to a 10% improvement for a simulated European drive cycle, compared to a homogeneous DI gasoline engine [6]. The major challenges of HCCI are the control of ignition timing and the operation over a wide range of engine speed and loads [4]. Unlike diesel engines where auto-ignition and combustion phasing can be controlled by injection timing, HCCI is controlled primarily by in-cylinder temperature and temperature distribution. This requires variable exhaust gases re-injection (EGR) rates, as well as sophisticated variable-valve actuation and control systems. Because HCCI engines operate in a limited speed/load range, commercial applications are likely to operate in a "dual-mode" between HCCI and Spark Ignition (SI) application [1][4]. This dual-mode strategy has recently been demonstrated by a car manufacturer on two concept vehicles based on conventional, production-based models [15, 23][5]. HCCI implementation is thought to be about 5-10 years away from high-volume production.

CURRENT COSTS AND COST PROJECTIONS -

Several studies provide costs of the various advanced gasoline technologies. The costs vary depending on the definition of cost and method and assumptions used. A summary of the cost data can be found in Tables 2-4. ■ **The US EPA study in 2008** presented *incremental compliance costs* for each technology, which account for both the direct manufacturing costs and the indirect costs. Firstly, the piece costs for an individual piece of hardware or system (e.g. an intake cam phaser to provide VVT) are estimated, which is the price paid by the manufacturer to a Tier 1 component supplier. To these costs, an indirect cost mark-up factor of 50% is to be added to generate the *compliance costs* that are then compared to a baseline vehicle. The technologies covered in this study (priced in dollars and converted to euros[6]) include engine friction reduction (€0-88), VVT (€41-146, depending on mechanisms used), VVL (€118-883, depending on mechanisms used), cylinder deactivation (€142, for a large car only), Homogeneous DI (referred to as GDI-stoichiometric in the study, €85-368), stratified DI (referred to as GDI-lean burn in the study, €525 relative GDI-stoich), and downsizing with turbocharging (€84-483). This EPA study also suggests learning impact to enable lower per-unit cost of production as soon as manufacturers gain experience in production and improve in areas such as simplifying machining and assembly operations. The "learning rate" is expressed as a percentage reduction in costs for each doubling of production. The EPA suggests a 20% learning rate for all newly applied technologies. ■ **The joint TNO/IEEP/LAT study (2006)** presents cost data in the form of *additional manufacturers' costs* compared to 2002 baseline gasoline vehicles (small, medium to large, with 4/6 cylinder in-line and multipoint injection). The study provides technology costs and cost ranges for small and large cars, namely, engine friction reduction (€40-60); DI-homogeneous charge (€125-175); DI-stratified charge with lean burn (€320-480); medium (20%) and strong (≥ 30%) downsizing with turbocharging (€225-510); and VVT (€100-200).
■ **The IEA Energy Technology Perspective (2008)** suggests an incremental cost for both engine (incl. VVT, turbocharging and direct injection) and non-engine technologies (not discussed in this paper) ranging from €1960 to €2380 [16]. ■ In 2008, **EUCAR, CONCAWE and JRC** presented their price assumptions for key components, systems and technologies used in their economical assessment of the Tank-To-Wheel (TTW) study. The prices provided for these components are equivalent to *delivered costs to vehicle manufacturers* and no mark up to include further costs (e.g. warranty) is included. The study assumes a volume of more than 50,000 units per year, projected for beyond 2010. The components (and their price assumptions) covered in this study include friction improvement (€60), gasoline/spark-ignition direct injection (€500), turbocharging (€180), and 20% downsizing for gasoline/spark-ignition (€220) [21, 22].

POTENTIAL AND BARRIERS -

Major drivers for the development and the introduction of new engine technologies include the need to meet environmental goals (e.g. Kyoto Protocol) and legislations. There are several fuel economy and greenhouse gas (GHG) emissions standards for passenger cars currently being proposed, already established or in the process of revision around the world. The fuel economy standards include the US *Corporate Average Fuel Economy* (CAFE) programme and Japan's *Top Runner* energy efficiency programme. China, Taiwan and South Korea have also established mandatory fuel economy

[4] Spark Ignition (SI) application would be used at higher loads, at idle or when engine is started cold.
[5] These HCCI prototypes were built on the integration of other advanced engine technologies which include gasoline direct-injection and variable valve actuation technologies. They offer up to 15% improved fuel efficiency relative to a comparable PFI engine while only requiring conventional automotive exhaust after-treatment. However, a sophisticated controller using cylinder pressure sensor and other control algorithms are required to manage the HCCI combustion process.

[6] 0.7 Euros to the Dollar throughout this paper

Please send comments to Tom.Palmer@aeat.co.uk, Nikolas.Hill@aeat.co.uk, Johannes.VonEinem@aeat.co.uk, Yvonne.Li@aeat.co.uk (Authors), and to Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org), Project Coordinators

standards while Austria has called for a voluntary industrial agreement to reduce fleet average fuel consumption for passenger cars. The California Air Resources Board (CARB) has issued regulations limiting the fleet average GHG emissions (CO_2, CH_4, N_2O and HFCs) from passenger cars. The Canadian government also announced it will take measures to reduce GHG emissions, shifting from its earlier voluntary Company Average Fuel Consumption (CAFC) programme to mandatory regulatory programmes. In the European Union, the Commission has proposed new-car CO_2 regulations, which require a fleet average of 130g of CO_2 per kilometre to be achieved by all cars registered in the EU, and a long-term target of 95g/km for the year 2020 [17].

Approximately 46.6 million new passenger cars were sold worldwide in 2006, compared to 43.4 million in 2005 [18, 19]. Apart from the ongoing economic crisis, not only emerging economies but also OECD countries still show a strongly increasing car ownership rate [15]. Gasoline engines power the great majority of passenger cars in the world, especially in countries such as the US, Japan and China (although in Europe, new sales of diesel cars surpassed gasoline cars in 2006).

Advanced gasoline engines are expected to remain competitive in vehicle applications for the near future. If technologies to improve gasoline engines can obtain a better "cost to benefit" ratio in terms of CO_2 reduction, it will be commercially attractive to introduce them into the new car fleet mix. Moreover, they are more technically mature than hydrogen and electric vehicles and can be deployed instantly using the existing infrastructure. They can offer near-term solutions addressed to the climate issue, with affordable costs for customers. Market potential may vary between countries depending on availability, prices and the level of fuel duty between petrol, diesel and alternative fuels. A few technical bottlenecks remain for some of the technologies discussed such as the HCCI (CAI). Moreover, different advanced technologies are being studied to a greater or lesser extent by different companies. Some of these technologies are mutually exclusive while others can be additive (e.g. turbo-downsized GDI, GDI with VVT and VVL). Hybrid electric technology may also benefit from developments in advanced engines.

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Please send comments to Tom.Palmer@aeat.co.uk, Nikolas.Hill@aeat.co.uk, Johannes.VonEinem@aeat.co.uk, Yvonne.Li@aeat.co.uk (Authors), and to Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org), Project Coordinators

Table 2 – Summary Table: Key Data and Figures for Baseline and Advanced Gasoline Vehicles

Baseline Vehicles (Source [20])			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Gasoline		
Energy Output	Kilometres		
Base Energy Consumption (l/km)	0.062	0.072	0.111
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO2 and other GHG emissions, g/km	143.5	166.7	255.0
Costs			
Capital Cost, overnight, Euro/unit	10,279	16,643	25,505
O&M cost (fixed and variable), Euro/km	0.03	0.04	0.05
Economic Lifetime, yrs	12	12	12
Advanced Vehicles (Source [20])			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Gasoline		
Energy Output	Kilometres		
Base Energy Consumption (l/km)	0.055	0.064	0.097
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO2 and other GHG emissions, g/km	126.3	146.7	224.4
Costs			
Additional Capital Cost, overnight, Euro/unit	231 – 401	308 – 462	130 – 524
O&M cost (fixed and variable), Euro/km	0.03	0.04	0.05
Economic Lifetime, yrs	12	12	12

Table 3 – CO_2 Emission Reductions for Advanced Gasoline Technologies

CO_2 reduction (%)	EPA 2008 [1]		IEA 2005 [2]	IEA 2008 [3]	TNO/IEEP/LAT 2006 [4]			Drake and Haworth 2007 [5]
	Small	Large			Small	Medium	Large	
Reduced engine friction losses	1-3	1-3	2-4		3	4	5	
DI / homogeneous charge (stoichiometric)	1-2	1-2	12-15	3-5	3	3	3	3-5
DI/Stratified charge (lean burn/complex strategies)	9-12	10-14			10	10	10	8-12 (WG); 20 (SG)
Mild downsizing with turbocharging	6-9	6-9	2-4	2-3				
Medium downsizing with turbocharging					8.5	10	10	
Strong downsizing with turbocharging					12	12	12	
Variable Valve Timing	2-3	1-4	1.5-2.5	6-8	3	3	3	
Variable valve control	4-5	3-6	5-7		7	7	7	
Cylinder deactivation		6	6-8					
Controlled auto-ignition (CAI) /Gasoline HCCI dual-mode	11-14	11-14						20

Table 4 – Incremental Costs of Advanced Gasoline Technologies

	EPA 2008 [Euro] [1]		TNO/IEEP/LAT 2006 [Euro] [2]		
	Small	Large	Small	Medium	Large
Reduced engine friction losses	0-58	0-88	40	50	60
DI / homogeneous charge (stoichiometric)	85-294	143-368	125	150	175
DI / Stratified charge (lean burn / complex strategies)	610-819	668-893	320	400	480
Mild downsizing with turbocharging					
Medium downsizing with turbocharging			225	300	375
Strong downsizing with turbocharging			390	450	510
Variable Valve Timing	41-62	41-146	100	150	200
Variable valve control	118-419	172-883	300	350	400
Cylinder deactivation		142			
Controlled auto-ignition (CAI) /Gasoline HCCI dual-mode	270-478	416-641			

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