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ESCUELA DE INGENIERÍAS INDUSTRIALES

TRABAJO FIN DE MÁSTER

Evolution of mixture formation, combustion and exhaust gas treatment systems in gasoline engines according to the EURO standards EU3, EU4 and EU5

Evolución de sistemas de formación de mezcla, combustión y tratamiento de gases en motores de gasolina de acuerdo a las normas EU3, EU4 y EU5

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ABSTRACT

European emissions regulations for light-duty vehicles have developed over many years, with consequent continuous development of engine and emissions control technologies to meet the legislative requirements.

The development of spark ignition internal combustion engines technologies to overcoming the standards restrictions has had to be accomplished in parallel with its improvement to prevent neglecting performance and efficiency.

As standards become more strict, systems become more complex and must work together to get the required result. After treatment systems require an accurate control on mixture formation and combustion to be feasible their functionality; mixture formation requires a precise fuel injection system; and all these set of elements working together, couldn't exist without the electronic control.

Then these systems and techniques that were developed for the fulfillment of standards EU3 to EU5 be described.

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RESUMEN

La normativa europea de emisiones para los vehículos ligeros se ha desarrollado desde hace décadas, con el continuo desarrollo consecuente de las tecnologías en los motores y de control de emisiones para cumplir con los requisitos legales.

El desarrollo de los motores de combustión por chispa de para superar las restricciones normativas ha tenido que llevarse a cabo en paralelo con su mejora para evitar dejar de lado el rendimiento y la eficiencia.

Los países de la Unión Europea (y también los que conforman el Espacio Económico Europeo) siguen los llamados **European emission standards** (Normas Europeas de Emisiones), en las que se regulan los límites de emisiones. A lo largo de los años se han actualizado éstas normas por medio de direcitvas.

Este trabajo se centra en los límites de emisiones impuestos a los motores de gasolina, por las directivas Euro 3, Euro 4 y Euro 5; y qué tecnologías han sido necesarias introducir por los fabricantes para poder superarlas.

Euro 1 (1993)	**Euro 2** (1996)	**Euro 3** (2000)	**Euro 4** (2005)	**Euro 5** (2008/9)	**Euro 6** (2014)
Para vehículos de pasajeros 91/441/EEC (93/59/EEC)	Para vehículos de pasajeros cars 94/12/EC (96/69/EC)	Para cualquier vehículo 98/69/EC. Para motocicletas 2002/51/EC (row B) 2006/120/EC	Para cualquier vehículo 98/69/EC (2002/80/EC)	Para vehículos de pasajeros ligeros y vehículos comerciales 715/2007/EC	Para vehículos de pasajeros ligeros y vehículos comerciales 715/2007/EC

Tabla I.I- Directivas de emisiones Europeas.

En la figura I, se puede apreciar la drástica reducción aplicada por la norma a lo largo de los años.

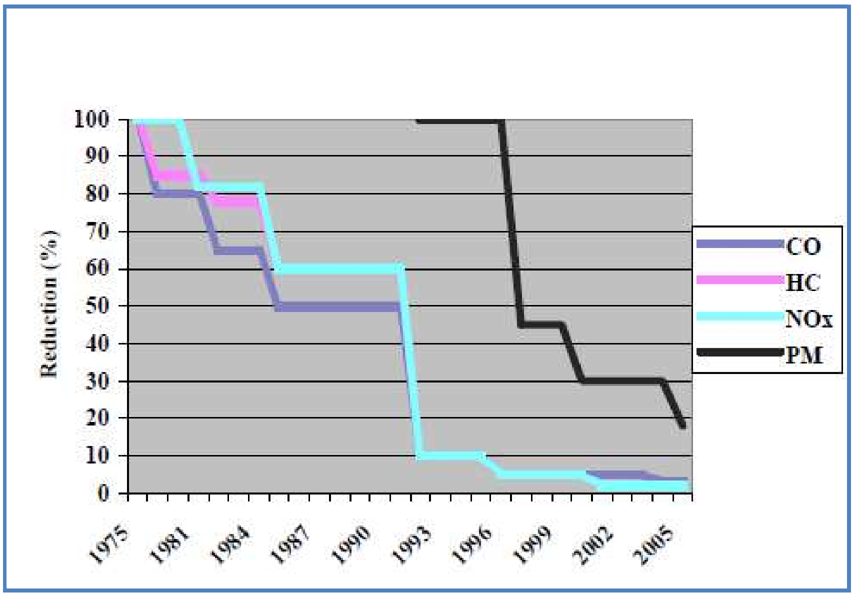

Figure I.I – Reducción de emisiones debidas a las normas Euro para vehículos de gasolina.

Como normas se vuelven más estrictas, los sistemas se vuelven más complejos y deben trabajar en paralelo para obtener el resultado requerido y no dejar de lado el rendimiento para cumplir con la norma.

El desarrollo tecnológico en motores de combustión interna de gasolina tiene tres vías diferenciadas:

- Sistemas de formación de la mezcla.
- Sistemas de combustión.
- Sistemas de post-tratamiento de gases de escape.

En la tabla I.II se aprecian las normas Euro y los sistemas introducidos en cada uno de sus periodos de aplicación para poder superarla.

Euro 3 (2000)	**Euro 4** (2005)	**Euro 5** (2008/9)
• *PFI* • *Wall-guided DIG* • *Closed loop* • *Electronic EGR* • *Port deactivation* • *Closed coupled cat*	• *PFI* • *Homogenous DIG* • *Closed loop (O2 or WR)* • *Hybrids* • *ETC* • *80 mJ Ignition* • *VVT (hydraulic)* • *Close coupled cat*	• *PFI* • *Homogeneous DIG* • *Spray stratified DIG* • *Alt fuels (CNG, ethanol)* • *Hybrids* • *Closed loop (O2 or WR)* • *ETC* • *Mixture motion* • *VVT (hydraulic)* • *Boosting* • *VVL (discrete)* • *80mJ ignition (multi-strike)* • *Closed coupled cat* • *NOx Trap*

Tabla I.II– Incremento del contenido tecnológico de acuerdo a la introducción de las normas Euro.

Inyección multipunto: Se deja atrás as los complejos y menos eficientes carburadores para optar por sistemas de inyección que permiten la dosificación precisa de combustible para el correcto funcionamiento de los sistemas de post-tratamiento de gases de escape.

Closed loop (lazo cerrado): Es necesaria la interconexión mediante sensores de los sistemas de alimentación y post-tratamiento de gases mediante sensores y controlados por la Unidad de Control Electrónico.

Desactivación de puerto: En motores multivávulas, para evitar que el descenso de la velocidad de entrada de aire a bajo régimen de motor, incida en la formación de la mezcla, se cierra total o parcialmente parte de la admisión para generar aumento de velocidad, mayor turbulencia y mejora de la mezcla aire combustible.

Control electrónico del acelerador: Este Sistema determina el flujo de aire apropiado y consecuentemente el correcto ángulo de mariposa para entregar el par demandad por el conductor, y el consiguiente ahorro de combustible

Modos de combustión con carga homogénea y con carga estratificada: Se ha visto que los modos de combustión con carga estratificada en gasolina, son adecuados para zonas de baja carga, y que reducen significativamente el consumo de combustible y por ende, de CO_{2}.. Los modos de carga homogénea son menos eficientes a baja carga pero mayores a alta. Algunos fabricantes como Mitsubishi, han desarrollado sistemas mixtos para aprovechar los beneficios de ambos modos.

VVT (sistema de sincronización variable de válvulas): permite incrementar el par y la potencia, haciendo el motor más eficiente. El overlap (cruce de las válvulas), es el tiempo que permanecen abiertas las válvulas de admisión y escape al mismo tiempo. Menor overlap produce una menor velocidad idle (ralentí) y mayor par a baja velocidad, pero un desempeño pobre a alta velocidad porque no se tiene el suficiente aire para una buena combustión. Mayor overlap genera un buen rendimiento a altas velocidades pero bajo rendimiento a bajas velocidades, produciendo altas emisiones contaminantes. Los motores, en los que no cambia el overlap, están diseñados para lograr la mayor eficiencia a una velocidad (80 – 95 Km/hr), sin embargo por debajo o por arriba de esta velocidad pierden eficiencia. Dado lo anterior, si se cambia el tiempo de apertura de alguna de las válvulas para que el overlap sea pequeño a bajas velocidades y grande a altas velocidades, se tendrá un motor más eficiente a baja y a alta velocidad. Los motores VVT cambian el overlap haciendo que el motor sea entre un 10% y un 20% más eficiente.

Catalizador: Para aquellas emisiones que no son posible reducir en la cámara de combustión, se hace necesario el uso de un sistema que intervenga antes de la expulsión de gases en el ambiente. Los catalizadores, son elementos capaces de acelerar las reacciones químicas de oxidación y reducción de los elementos nocivos en lo gases de escape. Son elemento complejos en cuanto a su construcción, caros por sus componentes, pero hoy en día imprescindibles para el cumplimiento de la norma.

Todos estos nuevos sistemas introducidos, cada cual más complejo, necesitan la interconexión entre ellos para poder funcionar de manera adecuada.

La adición de sensores y elementos electrónicos ha sido paralela a la de estos sistemas, y además los elementos de control imprescindibles para su funcionamiento.

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NOTATIONS AND ACRONYMS

ICE	Internal Combustion Engine	TDCO	Overlap at TDC
SUV	Sub Urban Vehicle	ITDC	Ignition at TDC
EPA	Enviromental Protection Agency	BDC	Bottom Dead Center
PM	Particulate Matter	IT	Ignition Point
THC	Total Hydrocarbon	λ	Excess Air Ratio
NMHC	Non-Methane Hydrocarbon	rfq	Relative fuel quantity
NOx	Nitrogen oxides	rac	Relative air charge
CO	Carbon monoxide	EGR	Exhaust Gas Recirculation
DI	Direct Injection	DIG	Direct Injection Gasoline
DISC	Direct Injection Stratified Charge		
PN	Particle Number	ETC	Electronic Throttle Control
NEDC	New European Driving Cycle	PCV	Positive Crankcase Ventilation
MNEDC	Modified New European Driving Cycle	TBI	Throttle Body Injection
PFI	Port Fuel Injection	MPI	Multi-Point Fuel Injection
UDC	Urban Driving Cycle	A/F	Air Fuel Ratio
SI	Spark Ignition	ECU	Electronic Control Unit
I	Intake Valve	ETB	Electronic Throttle Body
IO	Intake Valve Opens	ESP	Electronic Stability Program
IC	Intake Valve Closes	ABS	Anti-lock Braking System
E	Exhaust Valve	CVT	Continuously Varying Transmission
EO	Exhaust Valve Opens	HEV	Hybrid Electric Vehicle
EC	Exhaust Valve Closes	VVT	Variable Valve Timing
TDC	Top Dead Centre	EMS	Engine Management System
OBD	On Board Diagnostics	SOHC	Single Overhead Camshaft

Contents

1 FOREWORD

1.1 *General context*

Due to its impact on human health and the nature surrounding us, engine emissions have been significantly reduced over the last decades. This reduction has been enforced by the legislating organs around the world that gradually have made the manufacturers transform their engines to today’s complex high-Tech products.

The strategy of progressively tighter standards and regulations for emissions from conventional motor vehicles has worked well in terms of reduced vehicle emissions of local and regional air pollutants.

Over the last years, tighter standards have led to progressive improvements in vehicle technology. Improved engine technologies and fuels have contributed to significant reductions in emissions of local air pollutants from new vehicles. Gasoline vehicles sold in Europe from 2000 onwards (and thus meeting “Euro 3” standards) emit around 90% less CO, NOx and HC than vehicles sold in the 1980s, and emissions from new diesel vehicles have also been reduced significantly. This has contributed to reductions in local pollutants as newer vehicles with lower emissions have replaced older, more polluting vehicles. In most OECD countries, fleet emissions of NOx, CO and HC were at their highest levels in the early 1990s. Since then, they have dropped significantly (by 20-50%), despite a continuous increase in vehicle-kilometres travelled (+25% between 1990 and 2000). The overall result illustrates that technological improvements have made a significant contribution to improvements in local air quality in most OECD countries over this period. [1]

The vehicle emission standards have been tightened further since then. After the programmed introduction of these new standards (and equivalent standards adopted in other countries), all new conventional gasoline and diesel vehicles that meet these tighter standards will be extremely low emitters (and therefore “near clean”) in terms of local air pollutants. The expected availability of conventional motor vehicles with such low emissions of local pollutants is an important development that significantly improves the prospects for widespread use of low-emission vehicles in future.

Conventional gasoline vehicles meeting Euro 4 and/or Tier 2 standards can be readily regarded as low-emission vehicles in an air pollution sense. With respect to diesel vehicles, this may also be the case, depending on whether they are supplied to the market with advanced after-treatment systems (diesel engines may be able to meet Euro 4 standards without particulate filter traps or de-NO_x devices). With the application of exhaust after-treatment and filter traps, light-duty diesel vehicles could perform as well as gasoline vehicles – even in terms of NO_x and PM emissions – and will therefore also be properly considered “low-emission vehicles”. [2]

As the programmed tightening in standards takes effect and older technology vehicles in current fleets are replaced with conventional vehicles with the best current technology, the improvements in per-vehicle emissions of local pollutants will continue and levels of local pollutant emissions from motor vehicle fleets will continue to fall.

Until year 2008 (EU5), the gasoline technology content has focused on emissions driven, while from that year has shifted to efficiency driven, that is to say, reduce fuel consumption and CO_2. This is because the number of CO_2 targets required before 2008 by the standard. On figure 1 are shown the EU fleet averages evolution.

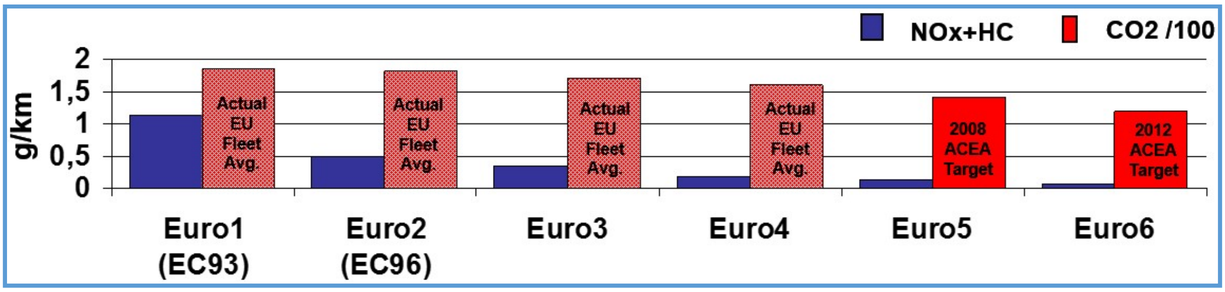


Figure 1.1 – EU fleet averages

1.2 *Purpose*

By this TFM is intended to show the *chronological evolution* of gasoline internal combustion engines (ICE), including subsystems, forced to be cleaner by the changes imposed for European standards, from EU3 to EU5. All this throughout the perspective of manufacturers (Bosch, Delphy, BMW, Mitsubishi, Toyota, …).

During this period and nowadays, engine's research and development has moved to get these standards targets and not only performance.

All the systems and strategies used to aim the EU levels will be exposed and slightly explained to give the reader a global perspective of the changes introduced in gasoline ICE.

2 LITERATURE REVIEW

2.1 *Emission standards*

Emission standards are legal requirements governing air pollutants released into the atmosphere. These standards set quantitative limits on the permissible amount of specific air pollutants that may be released from specific sources over specific timeframes. They are generally designed to achieve air quality standards and to protect human health.

Focusing on regulating pollutants released by automobiles (motor cars), a vehicle emission performance standard is a limit that sets thresholds above which a different type of emission control technology might be needed. While emission performance standards have been used to dictate limits for conventional pollutants such as oxides of nitrogen and oxides of sulphur (NO_x and SO_x), this regulatory technique may be used to regulate greenhouse gasses, particularly carbon dioxide (CO_2). In the US, this is given in pounds of carbon dioxide per megawatt-hour (lbs. CO_2/MWhr), and kilograms CO_2/MWhr elsewhere.

The emissions legislation includes not only specific emissions limits, but also specific driving cycles and test procedures. Laws on emissions are introduced successively in stages and the limits are continuously decreasing.

There are three main bodies of legislation in the world shown in the next map:

- European, called Euro 1 to 6,
- United States, called Tier I or II,
- Japanese legislation.

Those regulations and standards are respectively compulsory in European countries (in fact not only European Union countries, but all countries belonging to the European Economic Space), United States of America and Japan. For other countries in the world, each country may have adopted one of those three regulations, at least as a reference and in most cases with a time delay on the enforcement dates. In the figure, the countries following the European legislation are in different darkness of blue. The countries following the US legislation are in different darkness of brown. The Japan-based legislation is currently followed by Japan and is represented here in green. Not all the countries are at the same limits but the goal is the same: to force the transport sector to produce cleaner vehicles. [3]

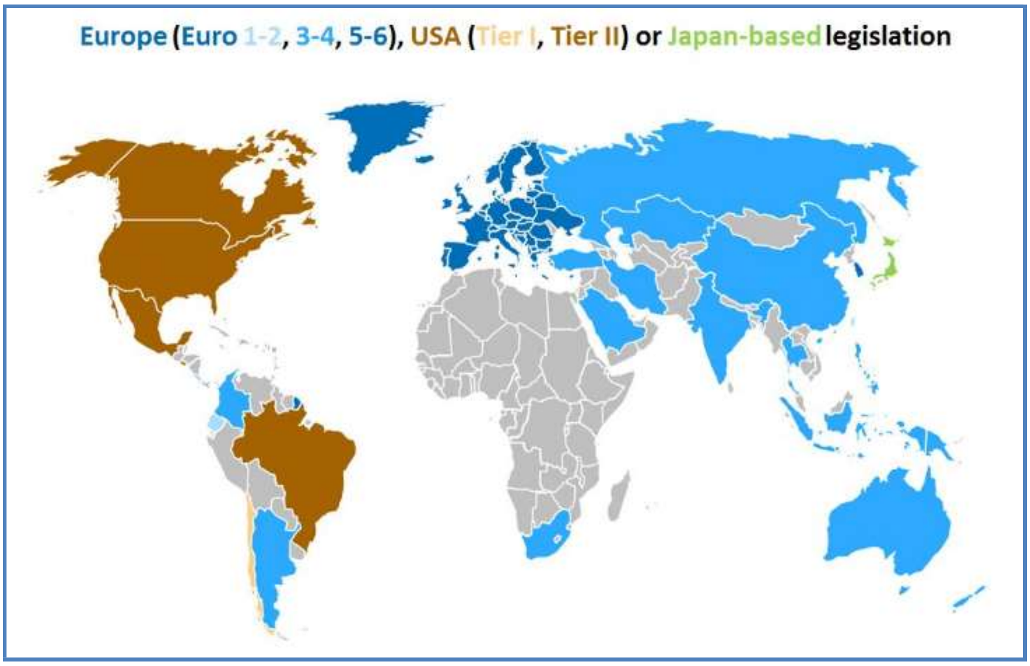


Figure 1.2 – Regulation distribution by country around the world.

In the **United States**, emissions standards are managed by the **Environmental Protection Agency** (EPA). The State of **California** has special vehicle emissions standards, and other states may choose to follow either the national or California standards. Federal (National) "Tier 1" regulations went into effect starting in 1994, and "Tier 2" standards are being phased in from 2004 to 2009. Automobiles and light trucks (SUVs, pickup trucks, and minivans) are treated differently under certain standards. The EPA has separate regulations for small engines, such as grounds-keeping equipment. The states must also promulgate miscellaneous emissions regulations in order to comply with the National Ambient Air Quality Standards.

European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards.

Starting June 10, 1968, the **Japanese Government** passed the *Japanese: Air Pollution Control Act* which regulated all sources of air pollutants. As a result of the 1968 law, dispute resolutions were passed under the 1970 *Japanese: Air Pollution Dispute Resolution Act*. As a result of the 1970 law, in 1973 the first release of four sets of new emissions standards was introduced. Interim standards were introduced on January 1, 1975 and again for 1976. The final set of standards were introduced for 1978.[10] While the standards were introduced they were not made immediately mandatory, instead tax breaks were offered for cars which passed them.[11] The standards were based on those adopted by the original US Clean Air Act of 1970, but the test cycle included more slow city driving to correctly reflect the Japanese situation.[12] The 1978 limits for *mean emissions* during a "Hot Start Test" of CO, hydrocarbons, and NO_x were 2.1 grams per kilometre (3.38 g/mi) of CO, 0.25 grams per kilometre (0.40 g/mi) of HC, and 0.25 grams per kilometre (0.40 g/mi) of NO_x respectively.[12] Maximum limits are 2.7 grams per kilometre (4.35 g/mi) of CO, 0.39 grams per kilometre (0.63 g/mi) of HC, and 0.48 grams per kilometre (0.77 g/mi) of NO_x. The "10 - 15 Mode Hot Cycle" test, used to determine individual fuel economy ratings and emissions observed from the vehicle being tested, use a specific testing regime. [13][14][15]

In 1992, to cope with NO_x pollution problems from existing vehicle fleets in highly populated metropolitan areas, the Ministry of the Environment adopted the *"Japanese: Law Concerning Special Measures to Reduce the Total Amount of Nitrogen Oxides Emitted from Motor Vehicles in Specified Areas",* called in short The Motor Vehicle NO_x Law. The regulation designated a total of 196 communities in the Tokyo, Saitama, Kanagawa, Osaka and Hyogo Prefectures as areas with significant air pollution due to nitrogen oxides emitted from motor vehicles. Under the Law, several measures had to be taken to control NO_x from in-use vehicles, including enforcing emission standards for specified vehicle categories.

The regulation was amended in June 2001 to tighten the existing NO_x requirements and to add PM control provisions. The amended rule is called the "Law Concerning Special Measures to Reduce the Total Amount of Nitrogen Oxides and Particulate Matter Emitted from Motor Vehicles in Specified Areas", or in short the Automotive NO_x and PM Law.

2.1.1 European standards

In Europe the evolutionary path initially lagged about ten years behind the United States. During the 1980s, some European countries adopted catalytic converters: Sweden, Switzerland, Austria, and a small proportion of new cars in Germany. In several other countries, the first catalytic converters emerged in the late 1980s under tax incentive programmes. It was not until the 1992 "**Euro 1**" legislation that the application of a closed loop-controlled three-way catalyst became the industry standard. From 1993 catalytic converters were required for all new gasoline cars sold in Europe (15 countries). Legislation in Europe subsequently became more stringent. In 1997, **Euro 2** became the standard, followed by **Euro 3** in 2000. In 2005 the next stage will be reached as **Euro 4** will replace the existing **Euro 3** standards. In contrast to the United States, Europe has a significant light-duty diesel fleet. In 2001, 34% of the new cars in Europe had diesel engines (up to 60% in France and Austria). Since the early 1990s diesel regulations have become progressively more stringent in Europe. The legal framework consists in a series of **directives**, each one an amendment to the 1970 Directive 70/220/EEC.

The following is a summary list of the standards, when they come into force, what they apply to, and which EU directives provide the definition of the standard (*Table 1.1*).

Euro 1 (1993)	**Euro 2** (1996)	**Euro 3** (2000)	**Euro 4** (2005)	**Euro 5** (2008/9)	**Euro 6** (2014)
For passenger cars 91/441/EEC (93/59/EEC)	For passenger cars 94/12/EC (96/69/EC)	For any vehicle 98/69/EC. For motorcycle 2002/51/EC (row B) 2006/120/EC	For any vehicle 98/69/EC (2002/80/EC)	For light passenger and commercial vehicles 715/2007/EC	For light passenger and commercial vehicles 715/2007/EC

Table 1.1 - European Standards directives.

Currently, emissions of nitrogen oxides (NO_x), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, lorries, trains, tractors and similar machinery, barges, but excluding seagoing ships and aeroplanes. For each vehicle type, different standards apply. Compliance is determined by running the engine at a standardised test cycle. Non-compliant vehicles cannot be sold in the EU, but new standards do not apply to vehicles already on the roads. No use of specific technologies is mandated to meet the standards, though available technology is considered when setting the standards. New models introduced must meet current or planned standards, but minor lifecycle model revisions may continue to be offered with pre-compliant engines. The trends in European rulemaking on emissions from new cars are outlined in Figure 1.3.

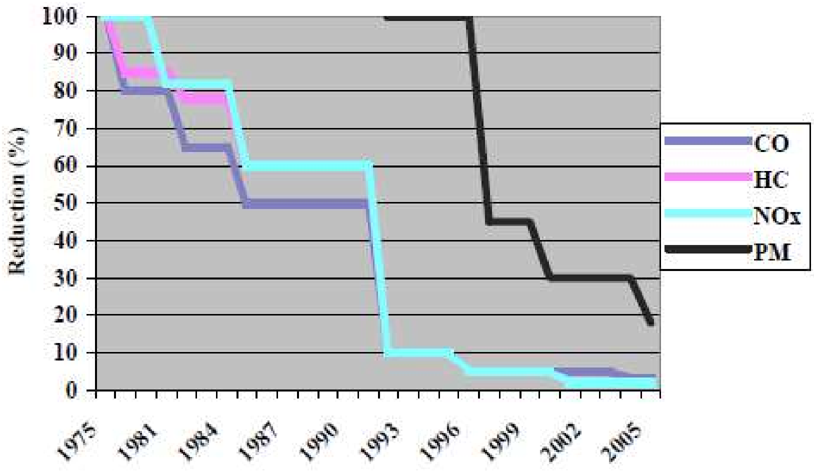


Figure 1.3 - Emission reduction due to ECE regulations (gasoline cars).

For petrol engine vehicles there was no limit on **particulate matter** until the Euro 5 step at which point a particulate matter (PM) weight limit was implemented for DI engines. In addition, a **particle number** (PN) limit has now been set for DI petrol engines, applicable from **Euro 6**. Nevertheless, all AECC tests included both PM and PN measurements to provide data on the development of particulate emissions from petrol engine vehicles. As might be expected, all results on the NEDC showed PM emissions from both PFI and DI vehicles to be within the Euro 5/6 limits applicable to DI engines.

European test cycle for passenger cars and LDTs

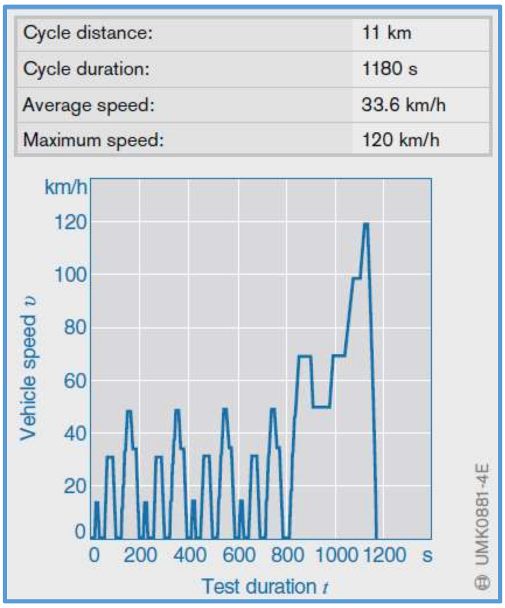
The modified new European driving cycle (MNEDC) has been in force since Euro 3. Contrary to the New European Driving Cycle (Euro 2), that only starts 40 seconds after the vehicle has started, the MNEDC also includes a cold-start phase.

The conditions for the procedure are: the vehicle is allowed to start at an ambient temperature of 20 to 30 °C for a minimum period of 6 hours. Since 2002 the starting temperature for Type VI testing has been lowered to – 7 °C.

To analyse the pollutants, exhaust gas is collected in bags during two phases:

- Urban Driving Cycle (UDC) at a maximum of 50km/h
- Extra-urban cycle (EUDC) at speeds up to 120km/h

The pollutant mass measured by analysing the bag contents is referred to the distance covered.



Cycle distance:	11 km
Cycle duration:	1180 s
Average speed:	33.6 km/h
Maximum speed:	120 km/h

Figure 1.4 - MNEDC for passenger cars and light-duty trucks

2.2 *Gasoline internal combustion engine. Spark ignition.*

The gasoline or spark-ignition (SI) internal combustion engine uses the Otto cycle and externally supplied ignition. It burns an air/fuel mixture and in the process converts the chemical energy in the fuel into kinetic energy.

For many years, the carburettor was responsible for providing an air/fuel mixture in the intake manifold which was then drawn into the cylinder by the downgoing piston.

The breakthrough of gasoline fuel injection, which permits extremely precise metering of the fuel, was the result of the legislation governing exhaust-gas emission limits. Similar to the carburettor process, with manifold fuel injection the air/fuel mixture is formed in the intake manifold.

Even more advantages resulted from the development of gasoline direct injection, in particular with regard to fuel economy and increases in power output. Direct injection injects the fuel directly into the engine cylinder at exactly the right instant in time.

In the next sections, the description of engine processes given by Reif (2015) will be used as bass. [10]

2.2.1 Method of operation

The combustion of the air/fuel mixture causes the piston (Fig. 2.1, Pos. 8) to perform a reciprocating movement in the cylinder. The name reciprocating-piston engine, or better still reciprocating engine, stems from this principle of functioning. The conrod converts the piston's reciprocating movement into a crankshaft rotational movement which is maintained by a flywheel at the end of the crankshaft. Crankshaft speed is also referred to as engine speed or engine rpm. [10]

Four-stroke principle

Today, the majority of the internal-combustion engines used as vehicle power plants are of the four stroke type. The four-stroke principle employs gas-exchange valves to control the exhaust-and-refill cycle. These valves open and close the cylinder's intake and exhaust passages, and in the process control the supply of fresh air/fuel mixture and the forcing out of the burnt exhaust gases. [10]

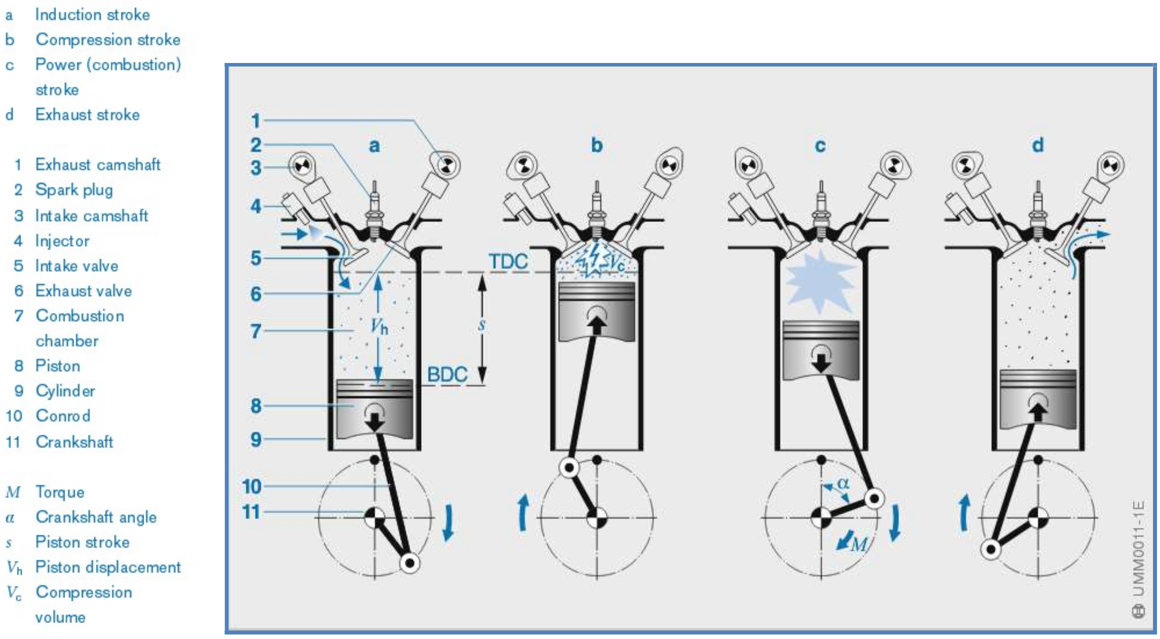


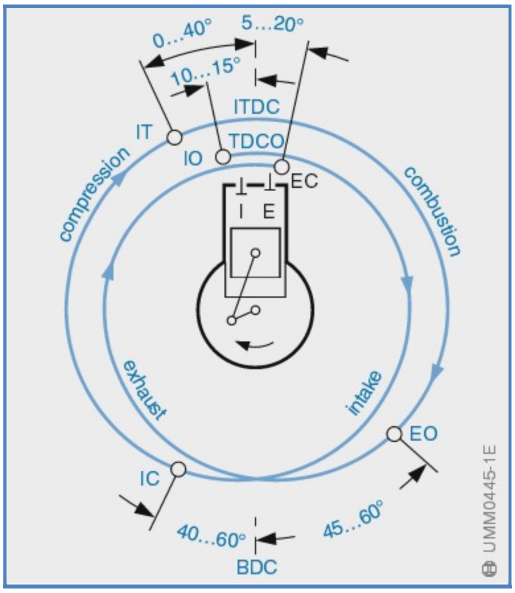
Figure 2.1 - Complete working cycle of the 4-stroke spark-ignition (SI) gasoline engine (example shows a manifold-injection engine with separate intake and exhaust camshafts). [10]

2.2.2 Valve timing

The gas-exchange valves are opened and closed by the cams on the intake and exhaust cam shafts.

On engines with only 1 camshaft, a lever mechanism transfers the cam lift to the gas-exchange valves. The valve timing defines the opening and closing times of the gas-exchange valves. Since it is referred to the crankshaft position, timing is given in "degrees crankshaft". Gas flow and gas-column vibration effects are applied to improve the filling of the combustion chamber with air/fuel mixture and to remove the exhaust gases. This is the reason for the valve opening and closing times overlapping in a given crankshaft angular-position range.

The camshaft is driven from the crankshaft through a toothed belt (or a chain or gear pair). On 4-stroke engines, a complete working cycle takes two rotations of the crankshaft. In other words, the camshaft only turns at half crankshaft speed, so that the step-down ratio between crankshaft and camshaft is 2:1.



I	Intake valve
IO	Intake valve opens
IC	Intake valve closes
E	Exhaust valve
EO	Exhaust valve opens
EC	Exhaust valve closes
TDC	Top Dead Center
TDCO	Overlap at TDC
ITDC	Ignition at TDC
BDC	Bottom Dead Center
IT	Ignition point

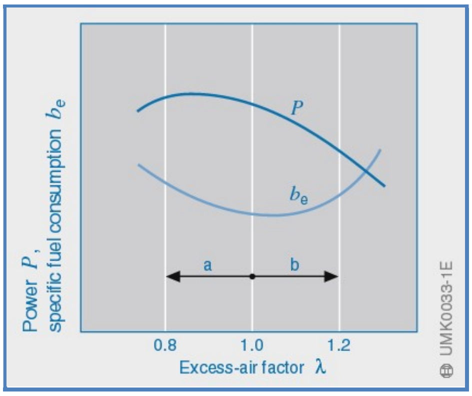
Figure 2.2 - Valve timing diagram for a four-stroke gasoline-engine. [10]

2.2.3 Air/fuel ratio

Complete combustion of the air/fuel mixture relies on a stoichiometric mixture ratio. A stoichiometric ratio is defined as 14.7 kg of air for 1 kg of fuel, that is, a 14.7 to 1 mixture ratio. The air/fuel ratio λ (lambda) indicates the extent to which the instantaneous monitored air/fuel ratio deviates from the theoretical ideal:

$$\lambda = \frac{induction\ air\ mass}{theoretical\ air\ requirement}$$

The lambda factor for a stoichiometric ratio is $\lambda = 1.0$. It is also referred to as the excess-air factor. Richer fuel mixtures result in λ figures of less than 1. Leaning out the fuel produces mixtures with excess air: λ then exceeds 1. Beyond a certain point the mixture encounters the lean-burn limit, beyond which ignition is no longer possible. The excess-air factor has a decisive effect on the specific fuel consumption (Fig. 2.3a) and untreated pollutant emissions (Fig. 2.3b).



a	Rich air/fuel mixture (air deficiency)
b	Lean air/fuel mixture (excess air)

Figure 2.3a - Influence λ on the power and on the specific fuel consumption under conditions of homogeneous air/fuel-mixture distribution. [10]

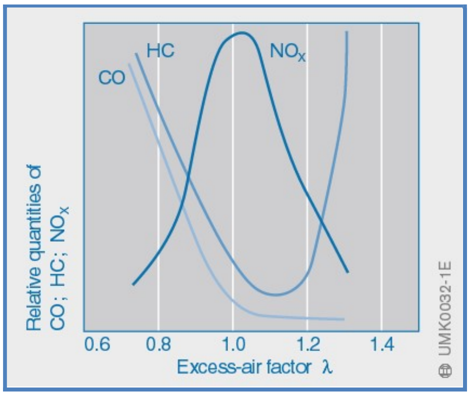


Figure 2.3b - Effect of λ on the pollutant composition of untreated exhaust gas under conditions of homogeneous air/fuel-mixture distribution. [10]

2.2.4 Induction-mixture distribution in the combustion chamber

Homogeneous distribution

The induction systems on engines with manifold injection distribute a homogeneous air/fuel mixture throughout the combustion chamber. The entire induction charge has a single excess-air factor λ (Fig.2.4a). Lean-burn engines, which operate on excess air under specific operating conditions, also rely on homogeneous mixture distribution.

Stratified-charge concept

A combustible mixture cloud with $\lambda \approx 1$ surrounds the tip of the spark plug at the instant ignition is triggered. At this point the remainder of the combustion chamber contains either non-combustible gas with no fuel, or an extremely lean air/fuel charge. The corresponding strategy, in which the ignitable mixture cloud is present only in one portion of the combustion chamber, is the stratified-charge concept (Fig. 2.4b). With this concept, the overall mixture – *meaning the average mixture ratio within the entire combustion chamber* – is extremely lean (up to $\lambda \approx 10$). This type of lean operation fosters extremely high levels of fuel economy.

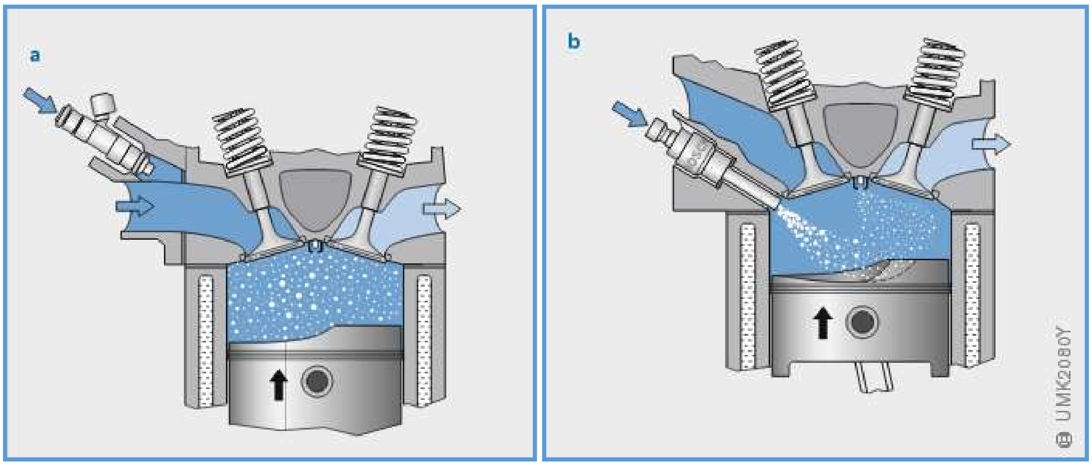


Figure 2.4- Induction-mixture distribution in the combustion chamber. [10]

Efficient implementation of the stratified charge concept is impossible without direct fuel injection, as the entire induction strategy depends on the ability to inject fuel directly into the combustion chamber just before ignition.

2.2.5 Ignition and flame propagation

The spark plug ignites the air/fuel mixture by discharging a spark across a gap. The extent to which ignition will result in reliable flame propagation and secure combustion depends in large part on the air/fuel mixture λ, which should be in a range extending from λ =0.75...1.3. Suitable flow patterns in the area immediately adjacent to the spark-plug electrodes can be employed to ignite mixtures as lean as $\lambda \leq 1.7$.

The initial ignition event is followed by formation of a flame-front. The flame front's propagation rate rises as a function of combustion pressure before dropping off again toward the end of the combustion process. The mean flame front propagation rate is on the order of 15...25 m/s. The flame front's propagation rate is the combination of mixture transport and combustion rates, and one of its defining factors is the air/fuel ratio λ. The combustion rate peaks at slightly rich mixtures on the order of λ =0.8...0.9. In this range it is possible to approach the conditions coinciding with an ideal constant-volume combustion process. Rapid combustion rates provide highly satisfactory full-throttle, full-load performance at high engine speeds.

Good thermodynamic efficiency is produced by the high combustion temperatures achieved with air/fuel mixtures of λ =1.05...1.1. However, high combustion temperatures and lean mixtures also promote generation of nitrous oxides (NO_x), which are subject to strict limitations under official emissions standards.

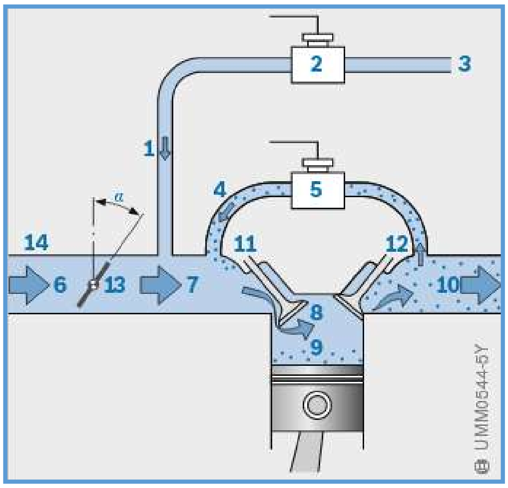
2.2.6 Cylinder charge

An air/fuel mixture is required for the combustion process in the cylinder. The engine draws in air through the intake manifolds (Fig. 2.5, Pos. 14), the throttle valve ensuring that the air quantity is metered. The fuel is metered through fuel injectors. Furthermore, usually part of the burnt mixture (exhaust gas) from the last combustion is retained as residual gas in the cylinder or exhaust gas is returned specifically to increase the residual-gas content in the cylinder.

Components of the cylinder charge

The gas mixture trapped in the combustion chamber when the intake valve closes is referred to as the cylinder charge. This is comprised of the fresh gas and the residual gas. The term "relative air charge *rac*" has been introduced in order to have a quantity which is independent of the engine's displacement. It describes the air content in the cylinder and is defined as the ratio of the current air quantity in the cylinder to the air quantity that would be contained in the engine displacement under standard conditions (p_0= 1013 hPa, T_0=273 K). Accordingly, there is a relative fuel quantity rfq; this is defined in such a way that identical values for rac and rfq result in λ = *1*, i.e., $\lambda = rac/rfq$, or with specified λ: $\mathrm{rfq} = \mathrm{rac}/\lambda$.

1 Air and fuel vapor (from evaporative-emissions control system)
2 Canister-purge valve with variable valve-opening cross-section
3 Connection to evaporative-emissions control system
4 Returned exhaust gas
5 Exhaust-Gas Recirculation valve (EGR valve) with variable valve-opening cross-section



6 Air-mass flow (ambient pressure p_a)
7 Air-mass flow (manifold pressure p_m)
8 Fresh-gas charge (combustion-chamber pressure p_c)
9 Residual-gas charge (combustion-chamber pressure p_c)
10 Exhaust gas (exhaust-gas back pressure p_e)
11 Intake valve
12 Exhaust valve
13 Throttle valve
14 Intake manifold

Figure 2.5 - Cylinder charge in a gasoline engine. [10]

Fresh gas

The freshly introduced gas mixture in the cylinder is comprised of the fresh air drawn in and the fuel entrained with it. In a manifold-injection engine, all the fuel has already been mixed with the fresh air upstream of the intake valve. On direct-injection systems, on the other hand, the fuel is injected directly into the combustion chamber. The majority of the fresh air enters the cylinder with the air-mass flow (Fig. 2.5, Pos. 6, 7) via the throttle valve. Additional fresh gas, comprising fresh air and fuel-vapor, is directed to the cylinder via the evaporative-emissions control system.

For homogeneous operation at $\lambda \leq 1$, the air in the cylinder directed via the throttle valve after the intake valve (11) has closed is the decisive quantity for the work at the piston during the combustion stroke and therefore for the engine's output torque. In this case, the air charge corresponds to the torque and the engine load. Here, changing the throttle-valve angle only indirectly leads to a change in the air charge. First of all, the pressure in the intake manifold must rise so that a greater air mass flows into the cylinder via the intake valves. Fuel can, on the other hand, be injected more contemporaneously with the combustion process and metered precisely to the individual cylinder. Therefore the injected fuel quantity is dependent on the current air quantity, and the gasoline engine is an air-directed system in "conventional" homogeneous mode at $\lambda \leq 1$.

During lean-burn operation (stratified charge), however, the torque (engine load) – *on account of the excess air* – is a direct product of the injected fuel mass. The air mass can thus differ for the same torque. The gasoline engine is therefore fuel-directed during lean-burn operation.

Almost always, measures aimed at increasing the engine's maximum torque and maximum output power necessitate an increase in the maximum possible fresh-gas charge. This can be achieved by increasing the engine displacement but also by supercharging.

Residual gas

The residual-gas share of the cylinder charge comprises that portion of the cylinder charge which has already taken part in the combustion process. In principle, one differentiates between internal and external residual gas. Internal residual gas is the exhaust gas which remains in the upper clearance volume of the cylinder after combustion or which, while the intake and exhaust valves are simultaneously open, is drawn from the exhaust port back into the intake manifold (internal exhaust-gas recirculation). External residual gas is exhaust gas which is introduced via an exhaust-gas recirculation valve (Fig. 2.5, Pos. 4, 5) into the intake manifold (external exhaust-gas recirculation).

The residual gas is made up of inert gas and – *in the event of excess air, i.e., during lean-burn operation* – of unburnt air. The amount of inert gas in the residual gas is particularly important. This no longer contains any oxygen and therefore does not participate in combustion during the following power cycle. However, it does delay ignition and slows down the course of combustion, which results in slightly lower efficiency but also in lower peak pressures and temperatures. In this way, a specifically used amount of residual gas can reduce the emission of nitrogen oxides (NO_x). This then is the benefit of inert gas in lean-burn operation in that the three-way catalytic converter is unable to reduce the nitrogen oxides in the event of excess air.

In homogeneous engine mode, the fresh-gas charge displaced by the residual gas (consisting in this case of inert gas only) is compensated by means of a greater opening of the throttle valve. With a constant fresh-gas charge, this increases the intake-manifold pressure, therefore reduces the throttling losses, and in all results in reduced fuel consumption.

3 REGULATION INCREASING TECHNOLOGY CONTENT (EU3 to EU5)

The development of technological content in gasoline ICE has three different paths:

- Mixture formation systems.
- Combustion systems.
- After-treatment exhaust gas systems

In the following table, is shown the different technologies introduced to achieve the requirements from Euro 3 to Euro 5. Most of the repeated systems have suffered an evolution and development during those years.

A clear example is the Port Injection System, that has evolved to Multi Point injection and finally to Direct Injection.

Euro 3 (2000)	**Euro 4** (2005)	**Euro 5** (2008/9)
• *PFI* • *Wall-guided DIG* • *Closed loop* • *Electronic EGR* • *Port deactivation* • *Closed coupled cat*	• *PFI* • *Homogenous DIG* • *Closed loop (O2 or WR)* • *Hybrids* • *ETC* • *80 mJ Ignition* • *VVT (hydraulic)* • *Close coupled cat*	• *PFI* • *Homogeneous DIG* • *Spray stratified DIG* • *Alt fuels (CNG, ethanol)* • *Hybrids* • *Closed loop (O2 or WR)* • *ETC* • *Mixture motion* • *VVT (hydraulic)* • *Boosting* • *VVL (discrete)* • *80mJ ignition (multi-strike)* • *Closed coupled cat* • *NOx Trap*

Table 3.1 – Regulation increasing technology content on gasoline engines.

3.1 *Multi-point fuel injection*

The emission requirements have increased the demands on fuel system control:

- With the introduction of the exhaust catalyst, the tailpipe emissions are been dramatically reduced. But this system has a problem. For maximum reaction efficiency, air fuel ratio must be accurately controlled.

  As is shown on figure 3.1, the variation range of lambda has to be very small if you want to maintain an acceptable conversion efficiency.

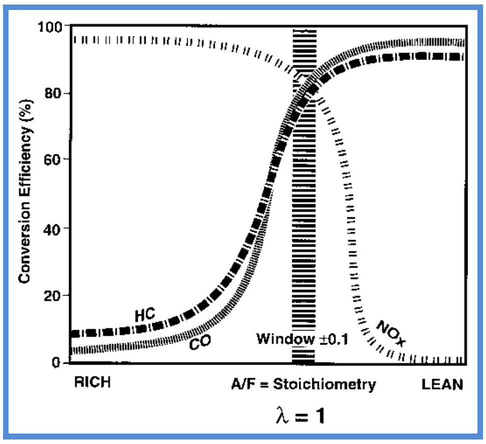


Figure 3.1 – Catalytic converter efficiency by mixture richness.

- The Air and fuel port distribution has become a critical factor not only for the use of catalyst. Other systems like PCV distribution (Positive Crankcase Ventilation), to reduce the effects of blow-by; EGR distribution (Exhaust Gas Recirculation); fuel rail flow distribution (Rail, Regulator, and Injector) need an accurate management.

  Typical required air fuel ratio distributions are +/- 0.5 A/F cylinder to cylinder. Control must be best during cold engine operating conditions. The relative quantity of fuel in the inducted mixture decreases (the mixture goes lean). This phenomenon stems from inadequate blending of air and fuel, low rates of fuel vaporization, and condensation on the walls of the inlet tract, all of which are promoted by low temperatures. To compensate for these negative factors, and to facilitate cold starting, supplementary fuel must be injected into the engine. This is why cold start is a critical operation due to the engine out emissions.

- To attain a complete combustion, good overall engine performance, and low emissions require having stoichiometric air fuel ratio, and a good atomized and vaporized fuel, because fuel in liquid state does not combust. Is the reason why is vital the fuel injector spray characteristics.

Gasoline injection systems, and electronic systems in particular, are better than old carburettors at maintaining air-fuel mixtures within precisely defined limits, which translates into superior performance in the areas of fuel economy, comfort and convenience, and power. The emission standards have led to a total eclipse of the carburettor in behalf of fuel injection.

The primary difference between carburettors and fuel injection is that fuel injection atomizes the fuel by forcibly pumping it through a small nozzle under high pressure.

Single-point fuel injection - *throttle body injection (TBI)* - is the concept behind this electronically-controlled injection system in which a centrally located solenoid operated injection valve mounted upstream from the throttle valve sprays fuel intermittently into the manifold. This manifold is the same as on a carburetted system, were almost a bolt-in replacement for the carburettor, so the automakers didn't have to make any drastic changes to their engine designs.

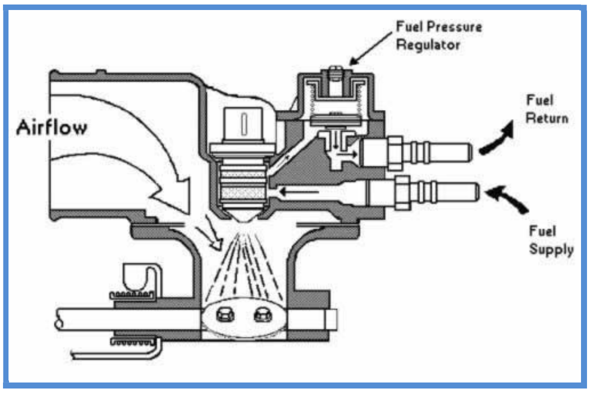


Figure 3.2 – Single-point fuel injection scheme.

Multipoint fuel injection forms the ideal basis for complying with the mixture formation criteria described above. In this type of system each cylinder has its own injector discharging fuel into the area directly in front of the intake valve.

Depending on the “electronification” grade, we can distinguish three types of systems:

- Mechanical injection systems: operates by injecting continually, without an external drive being necessary. Instead of being determined by the injection valve, fuel mass is regulated by the fuel distributor.
- Combined mechanical-electronic fuel injection: employs expanded data monitoring functions for more precise adaptation of injected fuel quantity to specific engine operating conditions.
- Electronic injection systems: featuring electronic control rely on solenoid-operated injection valves for intermittent fuel discharge. The actual injected fuel quantity is regulated by controlling the injector's opening time, with the pressure-loss gradient through the valve being taken into account in calculations as a known quantity. Full electronic injection systems have an integrated engine-management system.

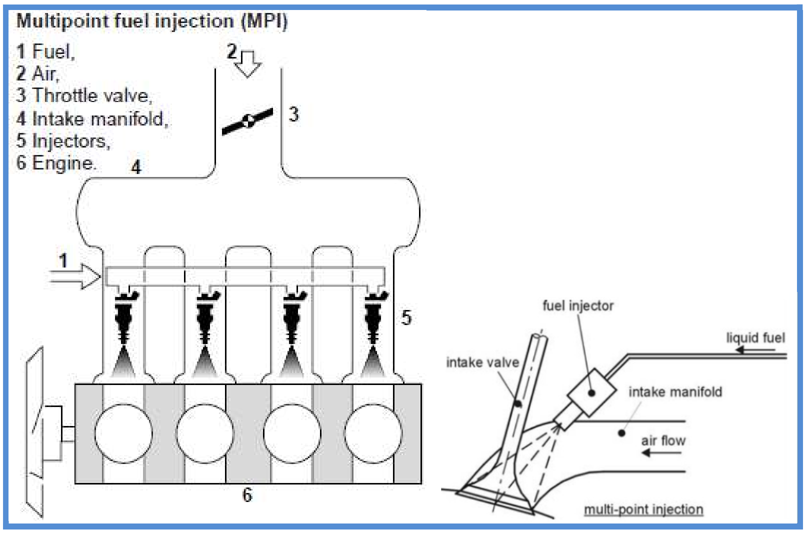


Figure 3.3 – Multipoint fuel injection scheme.

The evaporation and mixture formation outside the cylinder prevents large droplets from directly entering the combustion chamber. Those large drops enter the cylinder, may be deposited on the walls, due to the low pressure and density of the gas, and increase HC emissions.

3.2 *Direct injection gasoline*

Compared to the conventional diesel injection near top dead centre, the direct injection of gasoline may occur already during the induction stroke in the case of homogeneous mixture formation (full load), or very late during the compression stroke in the case of stratified charge operation (part load).

Direct fuel injection gasoline engines present a complex interdisciplinary task for the engine manufacturer. Constantly increasing demands require the simultaneous development of engine, catalytic converter, and electronic management technology in order to bring this new engine technology to a breakthrough. There are various competing approaches to solutions as far as further development in this field is concerned. An essential criterion required for improvements, is the lowest raw emissions at high operational stability. HC emissions are in this sense to be given the same priority as the NO_x. Combustion processes which include minimal wall wetting of the injected fuel principally demonstrate an advantage.

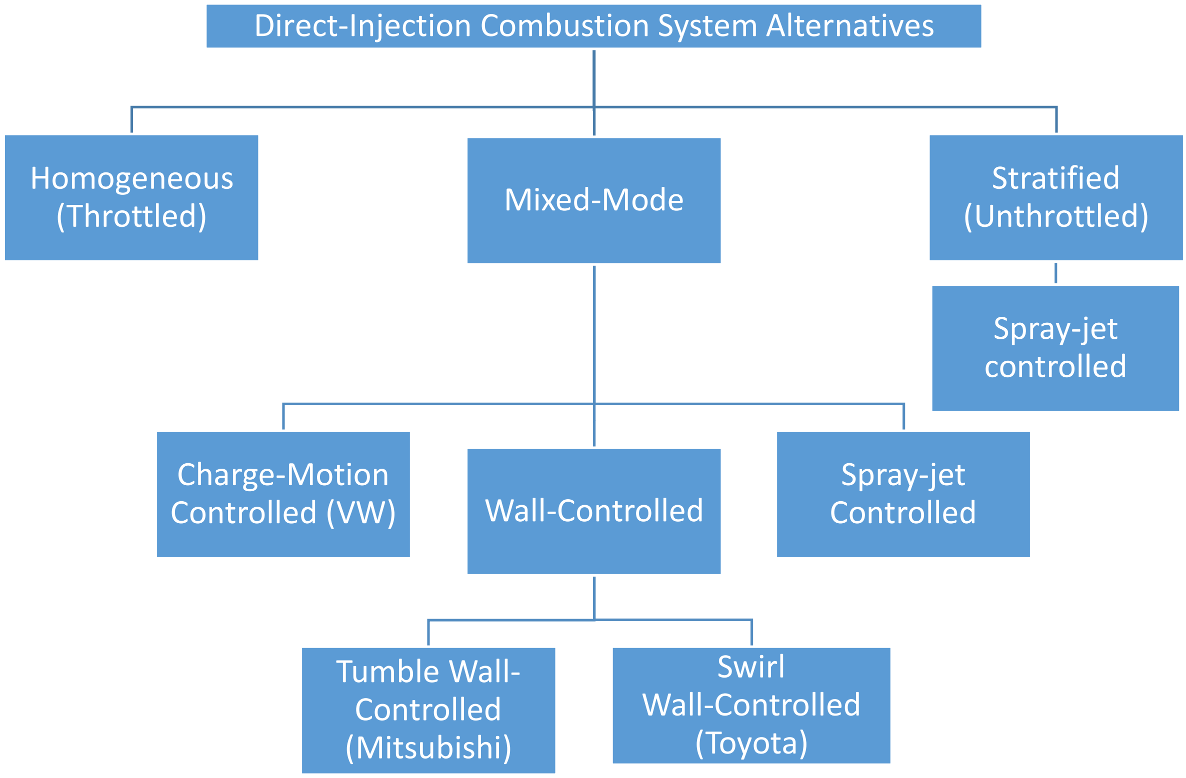


Figure 3.4 – Injection modes and alternatives on gasoline direct injection.

In 1996, the first modern gasoline direct injection automotive engine was introduced in Japanese market by Mitsubishi. Almost at the same time, Toyota introduced its own DI gasoline engines to the Japanese and European markets. These engines were designed to operate in stratified charge spark ignition combustion mode at part load and low to medium speed operations and in homogeneous charge spark ignition combustion mode at high load and high speed operations. Most other European and Japanese car manufacturers followed suit and produced their own DI gasoline engines or took licences from Mitsubishi. [12]

However, fuel efficiency in real world driving conditions was less than claimed because the use of expensive, bulky and less efficient lean-burn NO_x after-treatment for stratified lean-burn operations. Due to this, DI gasoline engines after 2001 have been designed to operate only in homogeneous charge mode, tuned and marketed for their high performance. Later, Toyota introduced a combination of direct injection and port injection to provide smooth operation with a stoichiometric mixture at part load conditions in the absence of large-scale charge motion.

Among other techniques like cylinder cut off or the application of variable valve trains , the direct injection of gasoline is the measure with the highest potential to reduce fuel consumption and thus also CO_2 emissions. Compared to a similar PFI engine, about 15–25% reduction of fuel consumption at part load are theoretically possible. Depending on the operating point of the engine, the direct injection of gasoline offers different advantages compared to the PFI technique.

The preliminary goal for a direct fuel injection system is therefore to be able to achieve the traditionally acceptable homogeneous A/F mixture state at the time of ignition, by promoting maximum A/F mixing, using a finely atomized spray, prevent wall wetting, injecting early during the intake stroke, having an efficient intake-port design, and a reliable injection location.

A simple summary of the HC/NOx problem:

- Hydrocarbons: The major source of engine-out hydrocarbon emissions is due to quenching of the flame in the overly lean fringes of the A/F cloud.
- Nitric-oxide: The major source of engine-out nitric-oxide emissions in stoichiometric combustion at local regions, within the combustion chamber.

In the figure 3.5 can appreciate the different combustion modes throughout the engine speed and load requirements.

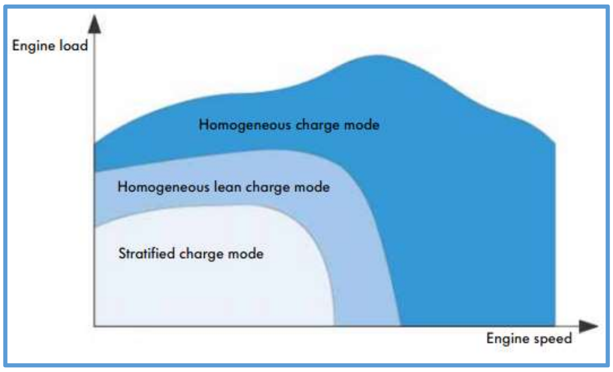


Figure 3.5 – Load vs speed charge mode.

3.2.1 Homogenous Direct Injection Gasoline

In this operation mode, the fuel is injected into the cylinder during the intake stroke and mixes homogeneously with the intake air. The engine runs at higher engines loads and speeds in homogeneous charge mode with an A/F ratio of λ=1.

An engine running in homogeneous charge mode operates in much the same way as an engine with intake manifold injection. The essential difference is that the fuel in the direct petrol injection engine is injected directly into the cylinder. Engine torque is determined by the ignition point (short term) and by the intake air mass (long term). In homogeneous charge mode, the ignition point is a major factor influencing engine torque, fuel consumption and emission behaviour. [14]

Advances in Direct Injection Gasoline (DIG) fuel systems and injectors enables the homogeneous-charge engine to have the potential of having lower emissions during cold and transient operation.

3.2.2 Direct Injection Stratified Charge (DISC)

By stratifying the A/F mixture in the centre of the combustion chamber and keeping the hot burnt products away from the walls, heat losses can be decreased. But against those benefits, we have a high risk of emissions formation, because the ideal properties of A/F cloud are difficult to attain, especially over entire load range. The excessive lean fringes of cloud extinguish to cause a HC emissions problem. The excessive stoichiometric regions of cloud cause NO_x emissions problem. Lean nature of combustion prevents use of a conventional 3-way catalyst (requires lean-NO_x catalyst).

Unthrottled, direct-injection, stratified-charge operation of a gasoline spark-ignited engine yields significant gains in thermal efficiency. This gain comes from a reduction or elimination of throttling losses, increased compression ratio and lean combustion. But, the challenge for the stratified-charge engine is to solve the high hydrocarbon emissions at light- loads and high nitric-oxide levels at mid-load.

The advances in control systems enables DI stratified charge engine to address the NOx emissions problem in new ways.

3.2.3 Mixed-mode Direct Injection Gasoline

Due to the advantages and disadvantages of stratified and homogeneous injection modes, a good solution could be the mixture, trying to get the best of both. [11]

Charge motion controlled

The charge motion controlled is dominated by interaction of bulk airflow with spray.

As advantages, the combustion rate scales better with engine speed, and combustion control over load-range is easier.

As disadvantages, the optimization over speed and load range is challenging, since spray is real-time event; potential for highly stratified operation may be limited.

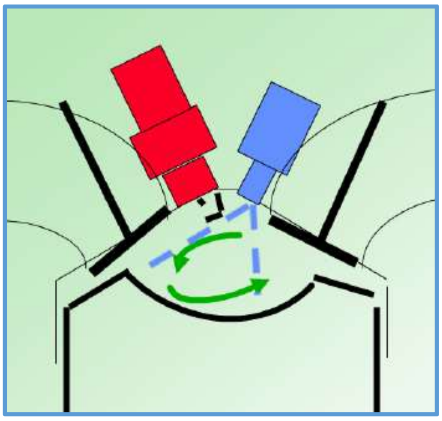


Figure 3.6 – Charge motion controlled direct injection scheme.

Wall Controlled

In this kind of injection mode, the mixture formation is dominated by the interaction of spray with the wall.

As advantages, the light-load stratification is easier to achieve. And the combustion is less sensitive to spray characteristics.

As disadvantages, the wall-wetting produced during cold and heavy-load operation causes HC emissions and smoke. Combustion modes are different in light-load and heavy-load regimes.

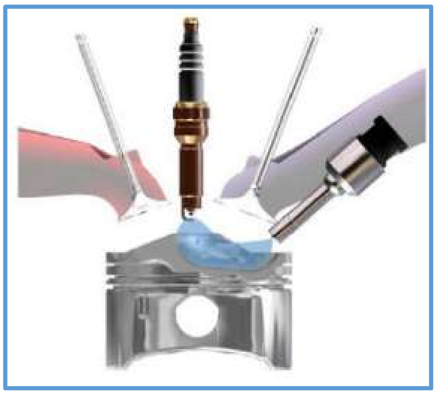


Figure 3.7 – Wall controlled direct injection scheme.

Spray-jet (or Puff) controlled

In this case, the process is dominated by spray characteristics.

As advantages, a potential for highly stratified operation is gotten.

As disadvantages, current sprays are not ideal (therefore usually requires deep bowl in piston for containment). It requires spraying directly onto spark-plug electrodes (therefore reduces the plug durability).

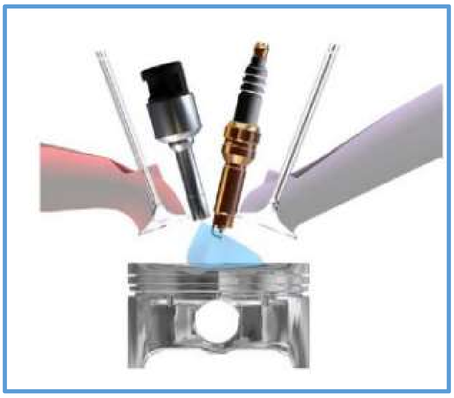


Figure 3.8 – Spray-jet direct injection scheme.

Due to the variety of possible operational modes the potential of DIG depends not only on the stratification and combustion characteristics, but also on the efficiency of the $DeNO_x$ catalyst technology and on the transient calibration. In addition to improvements in $DeNO_x$ catalyst, injection and ignition technology, *the development of suitable engine management strategies for optimum steady and transient state calibration of DIG vehicles will be a key issue in future development of DIG systems.*[15]

As conclusion, DI stratified charge gasoline engines have significantly higher fuel economy than conventional throttled engines; but they also have significantly higher HC and NOx emissions.

However, due to the advances in Direct-Fuel-Injection system technology, engine control systems, exhaust after-treatment systems and understanding of lean direct-injection combustion processes, revisiting the DI stratified charge has been done.

3.3 *Fuel control (closed loop)*

In order that the conversion rates of the three-way catalytic converter are as high as possible for the pollutant components HC, CO and NO_x, the reaction components must be present in the stoichiometric ratio. This requires a mixture composition of λ =1, the stoichiometric air/fuel ratio must be adhered to very precisely. Mixture formation must therefore be followed up in a control loop, because sufficient accuracy cannot be achieved solely by controlling the metering of the fuel.

Oxygen sensors monitor the amount of oxygen in the exhaust, and the engine control unit (ECU) uses this information to adjust the A/F ratio in real-time. It was not feasible to achieve this control with carburettors. There was a brief period of electrically controlled carburettors before fuel injection systems took over, but these electrical carbs were even more complicated than the purely mechanical ones. Oxygen sensor must reach operating temperature to enable corrections, typically 200-300°C.

The closed loop correction factor consists of two terms:

- Proportional term: Calibrated step change in fuelling each time a rich or lean error occurs. Size of step is intended to toggle oxygen sensor between rich and lean conditions.
- Integral correction term: Magnitude proportional to duration of error.

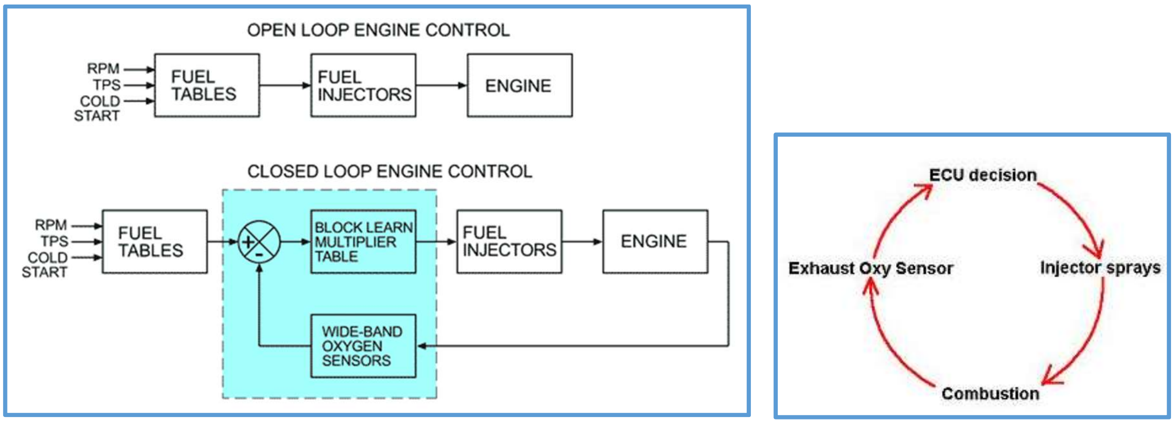


Figure 3.9 – Closed and open loop comparison (a). *Closed loop path diagram (b).*

The correction accuracy depends on control system's loop time, optimization of calibration and performance of components.

The adaptive multiplier corrects for long-term durability shifts of air and fuel components. Correction factors are partitioned in speed (rpm) / engine load blocks called cells.

Some limits exist for both closed loop and adaptive multiplier corrections. These limits must exceed normal fuel and air system variations. The resets of adaptive multipliers can cause fuelling errors and reset limits should be large enough to accommodate normal air and fuel system variations.

Therefore, the electronic systems that make up the closed loop are essential for the proper functioning of other corrective emissions elements like catalyst.

3.4 *Electronic Exhaust Gas Recirculation (EGR)*

The mass of the residual gas remaining in the cylinder, and with it the inert-gas content of the cylinder charge, can be influenced by varying the valve timing. In this case, one refers to internal EGR. The inertgas content can be influenced far more by applying "external" EGR with which part of the exhaust gas which has already left the cylinder is directed back into the intake manifold through a special line (Fig.3.10,Pos. 3). EGR leads to a reduction of the NO_x emissions and to a slightly lower fuel-consumption figure.

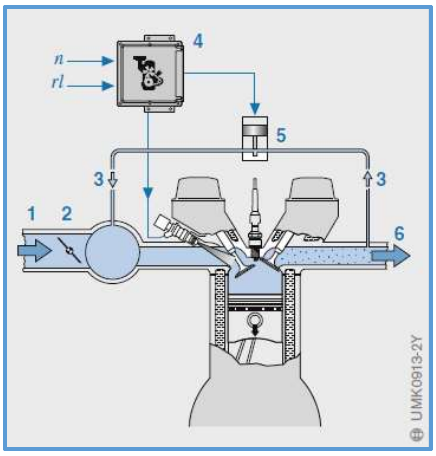


Figure 3.10 – Exhaust-Gas Recirculation (EGR). [10]

Limiting the NOx emissions

Since they are highly dependent upon temperature, EGR is highly effective in reducing NO_x emissions. When peak combustion temperature is lowered by introducing burnt exhaust gas to the air/fuel mixture, NO_x emissions drop accordingly.

Lowering fuel consumption

When EGR is applied, the overall cylinder charge increases while the charge of fresh air remains constant. This means that the throttle valve must reduce the engine throttling if a given torque is to be achieved. Fuel consumption drops as a result.

EGR: Method of operation

Depending upon the engine´s operating point, the engine ECU triggers the EGR valve and defines its opened cross-section. Part of the exhaust gas is diverted via this opened cross section and mixed with the incoming fresh air. This defines the exhaust-gas content of the cylinder charge.

EGR with gasoline direct injection

EGR is also used on gasoline direct-injection engines to reduce NO_x emissions and fuel consumption. In fact, it is absolutely essential since with it NO_x emissions can be lowered to such an extent in lean-burn operations that other emissions-reduction measures can be reduced accordingly (for instance, rich homogeneous operation for NO_x “Removal” from the NO_x accumulator type catalytic converter). EGR also has a favorable effect on fuel consumption.

There must be a pressure gradient between the intake manifold and the exhaust gas tract in order that exhaust gas can be drawn in via the EGR valve. At part load though, direct-injection engines are operated practically unthrottled. Furthermore a considerable amount of oxygen is drawn into the intake manifold via EGR during lean-burn operation.

Non-throttled operation and the introduction of oxygen into the intake manifold via the EGR therefore necessitate a control strategy which coordinates throttle valve and EGR valve. This results in severe demands being made on the EGR system with regard to precision and reliability, and it must be robust enough to withstand the deposits which accumulate in the exhaust-gas components as a result of the low exhaust-gas temperatures.

3.5 *Electronic Throttle Control (ETC)*

Torque Based Electronic Throttle Control (ETC) is a system that delivers through the transmission shaft output, the torque demanded by the driver. Driver demand is input by the Accelerator Pedal Position sensor and converted to a torque request. The system determines an appropriate airflow, and then the corresponding throttle angle, required to deliver the requested torque by the driver. Throttle angle is scheduled via ECU and delivered via an Electronic Throttle Body (ETB). Torque based ETC strategy was developed mainly to improve fuel economy. This is possible by not coupling the throttle angle to pedal position, which enables various fuel economy schemes and technologies.

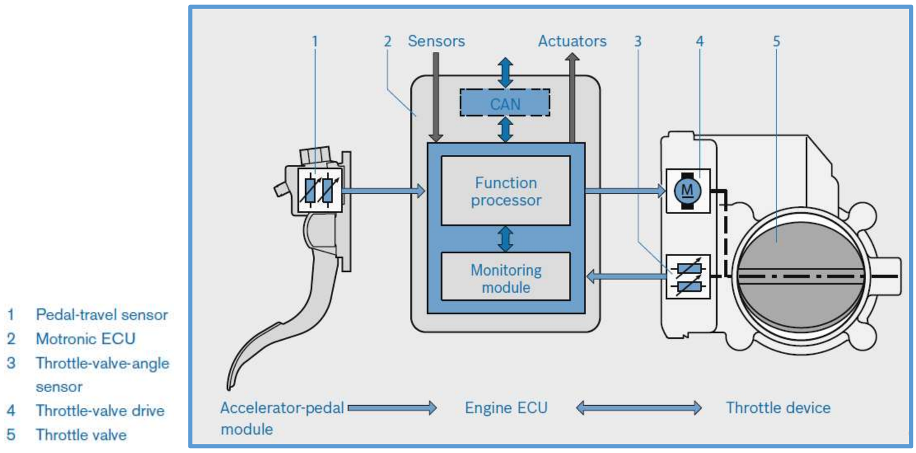


Figure 3.11 – Electronic throttle control
Bosch Professional Automotive Information

The reasons for using ETC are mainly:

- Enables many fuel economy and emissions, the throttle body will not have aggressive reactions from the driver, all aggressive actions are filtered by ECU and delivers smooth reactions.
- Improved driveability, for example overcome hesitation/delays related to manifold filling.
- Enables aggressive automatic transmission shift schedules (earlier upshifts and later downshifts). This is possible by adjusting the throttle angle to achieve the same wheel torque during shifts. In other words the engine shifts can result in an engine lugging condition (low engine speed and low manifold vacuum) while still delivering the same torque requested by the driver.
- Enables the ABS, ESP and traction control request of low torque from the engine.

Due to the introduction of this system, it is possible improvement technologies such as:

- Lean Burn and direct injection (deliver same torque during transitions and NO_x trap purging)
- Continuously varying Transmission (CVT)
- Hybrid Electric Vehicle (HEV)

Results in a less intrusive Vehicle and engine speed limiting, smoother traction control.

Other generic benefits of ETC are; eliminate cruise control actuators, eliminate Idle Control Bypass actuator, packaging (no gas pedal cable).

The system presented here is called ***torque based***, but the first generation, before torque based, had a similar hardware system but the software control was much simple. Normally just one map was used, a map from pedal position versus a desired throttle position, it is possible to say, it was one step forward of cable gas pedals. It had benefits in emissions but not like the torque based concept.

3.6 *Port deactivation*

One important feature of any engine is the swirl charge motion to promote the A/F mixture and vaporization, to obtain a more efficient mixing into the engine. Then, it is possible to reach more torque, emissions improvement and fuel economy.

The swirl charge motion is gotten with high intake air speed. It is necessary a small intake port to generate high air speed, it is found in engines with one valve per cylinder.

With engines evolution, increasing the number of intake valves give the ability to the engine intake more air quantity, but the side effect is reduction of air speed at low engine speed.

So that one valve per cylinder gives high speed air flow at low engine speed. It is interesting for low charge at high engine speed. Comparing with one valve, two valves per cylinder has the air speed lower at low engine speed; needs more turbulence in the air flow to get a good A/F mixture. The ideal engine would be an 8V at low and medium engine speed (emissions and fuel economy) and 16V at high engine speed (performance), in the case of a four cylinder engine. One way to “simulate” the 8 valves in one 16 valves engine is closing one intake valve from each cylinder, this work can be done throw an addition of one throttle per cylinder. See the picture below:

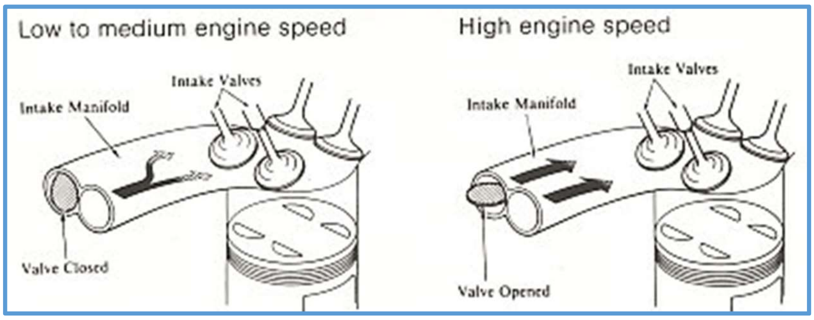


Figure 3.12 – Port deactivation comparison (low vs high engine speed).

Then these throttles are integrated into the intake manifold, controlled by engine ECU, in this way:

- Low rpm → Intake Port Closed
- Medium rpm → Intake Port partially Open
- High rpm → Intake Port Open

A typical example is Opel 1.6L 16V engine (fig. 3.13).

Figure 3.13 – Opel port deactivation system.

3.7 *Variable Valve Timing (VVT)*

In the 1960s, automakers began developing variable valve timing systems that allowed intake and exhaust valves to open earlier or later in the 4-stroke cycle. The aim was to improve volumetric efficiency, *decrease* NO_x *emissions*, and decrease pumping losses. Today, there are two major types of variable valve timing: cam phasing and cam changing. With cam changing, the ECU selects a different cam profile based on engine load and speed, whereas with cam phasing, an actuator rotates the camshaft, changing the phase angle.

3.7.1 Discrete VVT

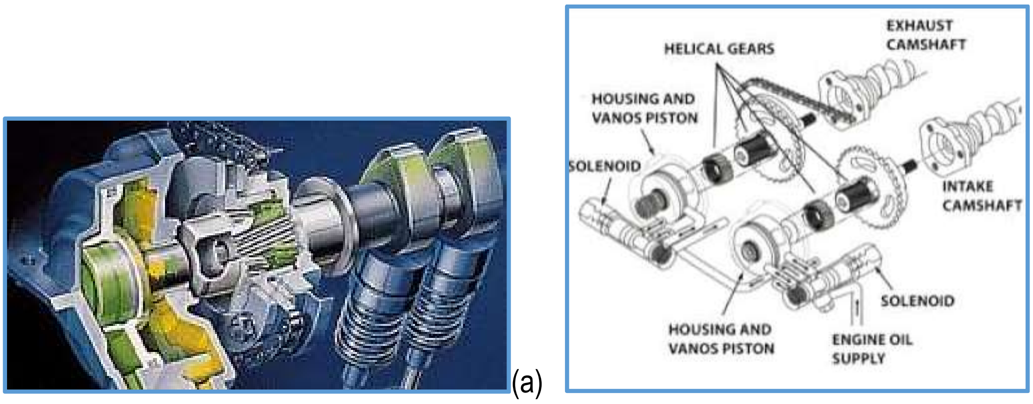
Is the simpler cam-phasing VVT system offer just 2 or 3 fixed phasing angles, such as either 0° or 30°. Better systems can vary phase angle continuously. Obviously, this provides the most suitable valve timing at any rev, thus greatly enhance engine flexibility. Moreover, the transition is seamless and hardly noticeable, contributing to refinement. Today, continuous systems have put discrete systems in extinction.

3.7.2 Hydraulic VVT

The cam-phasing VVT cannot vary the duration of valve opening. It just allows earlier or later valve opening. Earlier opening results in earlier closing, of course. It also cannot vary valve lift, unlike cam-changing VVT. However, cam-phasing VVT is the simplest and cheapest form of VVT because each camshaft needs only one hydraulic phasing actuator, unlike other systems that employ individual mechanism for every cylinder.

Some designs, such as BMW's Double-Vanos system, has cam-phasing hydraulic VVT at both intake and exhaust camshafts. This enables more overlapping, hence higher efficiency. This explain why BMW M3 3.2 (100hp/litre) is more efficient than its predecessor, M3 3.0 (95hp/litre) whose VVT is bounded at the inlet valves.

In the E46 3-series, the Double-Vanos shifts the intake and exhaust camshaft within a range of 40° and 25° respectively.



(a) (b)

Figure 3.14 – BMW "Vanos" Variable Timing system (a) and "bi-Vanos" (b)

From figure 3.14, it is easy to understand its operation. The end of intake camshaft incorporates a gear thread. The thread is coupled by a cap which can move towards and away from the camshaft. Because the gear thread is not in parallel to the axis of camshaft, phase angle will shift forward if the cap is pushed towards the camshaft. Similarly, pulling the cap away from the camshaft results in shifting the phase angle backward.

Whether push or pull is determined by the hydraulic pressure. There are two chambers right beside the cap and they are filled with liquid (these chambers are colored green and yellow respectively in the right picture). A thin piston separates these two chambers, the former attaches rigidly to the cap. Liquid enter the chambers via electromagnetic valves which controls the hydraulic pressure acting on each chambers. For instance, if the engine management system signals the valve at the green chamber open, then hydraulic pressure acts on the thin piston and push the latter, accompany with the cap, towards the camshaft, thus shifts the phase angle forward.

Continuous variation in timing is easily implemented by positioning the cap at a suitable distance according to engine speed.

The "Vanos" system works at intake camshaft only. However, it can be duplicated at the exhaust camshaft to provide a wider range of adjustment. BMW calls this "Double Vanos" or "Bi-Vanos" (fig3.14b).

Other VVT system developed by Nissan is VVEL (Variable Valve Event Lift), it performs similarly to BMW's Valvetronic system but with desmodromic control of the output cam (it can also modify the valve lift), allowing VVEL to operate at higher engine speeds (RPM). Other similar systems are offered Toyota (Valvematic).

Variable Valve Event Lift has the following benefits:

- Improved fuel efficiency and engine torque: fuel efficiency and engine torque have been improved by substantially reducing intake resistance, which conventionally occurs when the throttle valve of an engine running at low revs is closed.
- Improved throttle response: Throttle response has been improved by directly controlling the amount of intake with the intake valve rather than the throttle valve, where it has conventionally been controlled.
- Reduced HC emissions: By reducing the amount of valve lift when the engine is running at low revs, the intake flow rate is increased and full combustion becomes easier. This reduces emissions of hydrocarbon (HC), which can be produced during partial combustion cycles. [20]

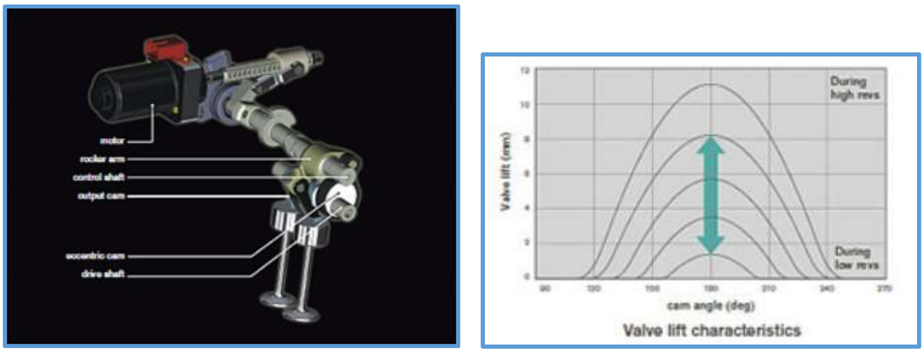


Figure 3.15 – Nissan VVEL system

A rocker arm and two types of links open the intake-valves by transferring the rotational movement of a drive shaft with an eccentric cam to the output cam. The movement of the output cam is varied by rotating the control shaft with a DC stepper motor and changing the fulcrums of the links. This makes the continuous adjustment of the amount of the valve's lift (e.g., the amount of intake opening), during the intake valve event in the four-stroke cycle, possible. CVTC and VVEL together control the valve phases and its valve events, allowing free-control of the valve timing and lift. This results in more efficient airflow to the cylinder, significantly improved responsiveness, optimizing the balance between power and environmental performance.

3.8 *Boosting*

When an engine has a supercharging system, normally the engine hardware modifications are; less displacement, fewer cylinders, less parts. As the result of these factors we get Less Engine Friction. Thus with less engine friction, the mechanical efficiency is improved. That leads in a reduction on CO_2 emission.

To get more efficiency from an engine, one way is increase the compression ratio and then get more combustion pressure. To get this higher compression ratio we can increase the air mass inside the cylinder, boosting is the solution to do that.

Boosting, increase the pressure in the intake manifold more than 100kPa, can be reached with turbocharger or supercharger.

Turbocharger: The compressor is driven via exhaust gas energy.

Supercharger: Compressor is driven mechanically by the crankshaft.

As the supercharger needs the connection with engine crank pulley to be driven, it spends energy from the engine, the turbocharger recycles the useless exhaust gas energy. So, turbocharger is more efficient than supercharger, this is the reason the turbo charger is so popular with down sized engines.

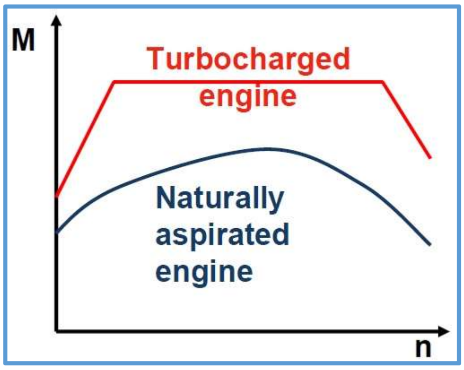


Figure 3.16 - Torque vs engine speed chart

Figure 3.16 show the increase of torque when turbocharger is used; with down sized engines the difference between the peak torque from aspirated engine to the flat torque from turbocharger is not so big, for example an 1.5 or 1.6L 4 cylinders aspirated engine against 1.0L 3 cylinders turbo. But the availability of torque at low engine speed and the highest efficiency is converted in the lower CO_2.

High altitude

Other important point of turbo charged engines is its operation at high altitude. It is possible to compensate the lack ambient pressure to keep the intake manifold pressure as in the sea level. It is possible adjust the waste gate valve, thanks to the Engine Management System (EMS). The vehicle has the same torque and efficiency at sea level until high altitudes. Then, the CO2 emissions is the same from the sea level until high altitudes.

3.9 *Closed coupled catalyzer*

Three-Way Catalysts (TWC) are the main technology used to control emissions from petrol engines. The catalyst uses a ceramic or metallic substrate with an active coating incorporating alumina, ceria and other oxides and combinations of the precious metals - platinum, palladium and rhodium. Three-way catalysts operate in a *closed-loop system* including a lambda or oxygen sensor to regulate the air/fuel ratio on petrol engines. The catalyst can then simultaneously oxidise CO and HC to CO2 and water while reducing NO_X to nitrogen.

Fast light-off catalysts allow the catalytic converter to work sooner by decreasing the exhaust temperature required for operation. Untreated exhaust emitted at the start of the legislated emissions test and on short journeys in the real world is curtailed. Changes to the thermal capacity of substrates and type and composition of the active precious metal catalyst have together resulted in big improvements. More thermally durable catalysts with increased stability at high temperature allow the catalytic converter to be mounted closer to the engine and increase the life of the catalyst, particularly during demanding driving conditions. Precious metal catalysts with stabilised crystallites and washcoat materials that maintain high surface area at temperatures around 1000°C are needed. Improved oxygen storage components stabilise the surface area of the washcoat, maximise the air/fuel "window" for three-way operation and indicate the "health" of the catalyst for On Board Diagnostic (OBD) systems.

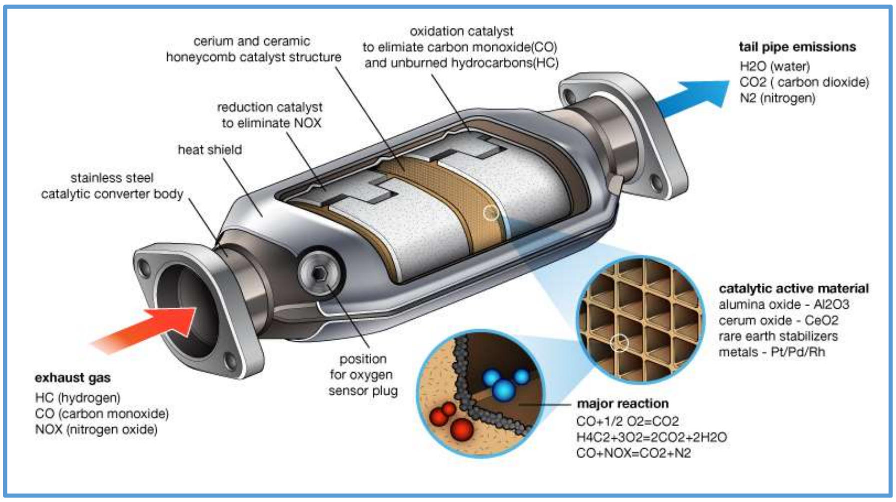


Figure 3.17 – Three way catalyst

"Close-coupled" catalysts mounted immediately after the engine exhaust manifold allow the catalyst to start working within seconds (faster light-off).

Figure 3.18 – Close-coupled catalytic converters, with underfloor catalyst and oxygen sensor.

3.10 *NO_x Trap*

There are specific situations where engine operating conditions may not be ideal for conventional catalysts to achieve their full potential. Three-way catalysts, for instance, are highly effective in petrol engine exhaust, but there is too much oxygen present in diesel exhaust for their NOx-reduction function to operate properly. Also catalysts generally need to reach a certain minimum temperature for effective operation, and although modern systems can reach this 'light-off' temperature within a few seconds there may still be some emissions until that temperature is reached. Adsorbers offer ways to collect certain pollutants, specifically NO_x or HC, during conditions which are not ideal, to store the pollutant and then to treat it when conditions are suitable. The two main current applications are NO_x adsorbers, which can be used to treat NO_x emissions from lean-burn petrol engines or from diesel engines and hydrocarbon adsorbers which can be used with conventional three-way catalysts to 'trim' the HC emissions from fuel enrichment needed for cold start.

NO_x adsorbers (NO_x traps) adsorb and store NO_x under lean conditions. A typical approach is to speed up the conversion of nitric oxide (NO) to nitrogen dioxide (NO2) using an oxidation catalyst so that NO2 can be rapidly stored as nitrate on alkaline earth oxides. A brief return to stoichiometric or rich operation for one or two seconds is enough to desorb (remove) the stored NO_x and provide the conditions for a conventional three-way catalyst mounted downstream to reduce (destroy) NO_x.

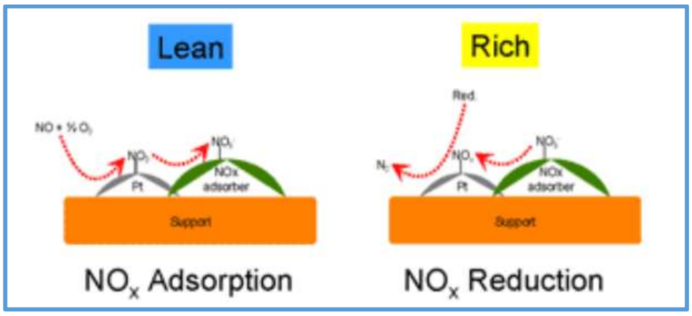


Figure 3.19 – NO_x trap reduction and oxidation process

Unfortunately, NOx adsorbers also adsorb sulfur oxides resulting from the fuel sulfur content. For that reason fuels with a very low sulfur content (European “zero” sulfur fuel contains less than 10 ppm sulfur) are required. The sulfur compounds are more difficult to desorb, so periodically the system has to automatically run a short “desulfation” cycle to remove them.

4 BMW M43/N42/N45 ENGINE EVOLUTION

The BMW M43 is a straight-4 SOHC piston engine which replaced the M40 and was produced from 1991-2002. Displacement ranges from 1.6 L to 2.0 L. The M43 powered base-model cars, while higher performance models at the time were powered by the DOHC M42 or M44.

Compared with its M40 predecessor, it features a *dual-path intake manifold* (called Individual Control Intake Manifold by BMW) to provide torque across a wider rev range, knock sensing and a timing chain (instead of the M40's timing belt).

In 1998 the displacement was increased to 1.9 litres, increasing torque to 180 Nm at 3900 rpm.

Models					
Engine	Displacement	Power	Torque	Redline	Year
M43B16	1596 cc	75 kW (101 hp) @ 5500	150 N·m (111 lb·ft) @ 3900	6200	1991
M43B18	1796 cc	85 kW (115 hp) @ 5500	168 N·m (124 lb·ft) @ 3900	6200	1993
M43B19	1895 cc	87 kW (118 hp) @ 5500	180 N·m (133 lb·ft) @ 3900	6200	1998
		77 kW (105 hp) @ 5300	165 N·m (122 lb·ft) @ 2500	6200	1999

Table 4.1 – BMW M43 models

M43B16

The 1.6 L (1596cc) M43B16 produces 102 hp and 150 Nm. It uses the Bosch Motronic 1.7.1 fuel injection system.

M43B18

The M43B18 has a 1796 cc displacement. It produces 115 hp and 168 Nm and uses the Bosch Motronic 1.7.1 fuel injection system.

M43B19

The M43B19 (also known as the "M43TÜ") is the largest M43 engine, with a displacement of 1895 cc. It produces up to 118 hp and 180 Nm and uses BMW BMS 46 fuel injection system.

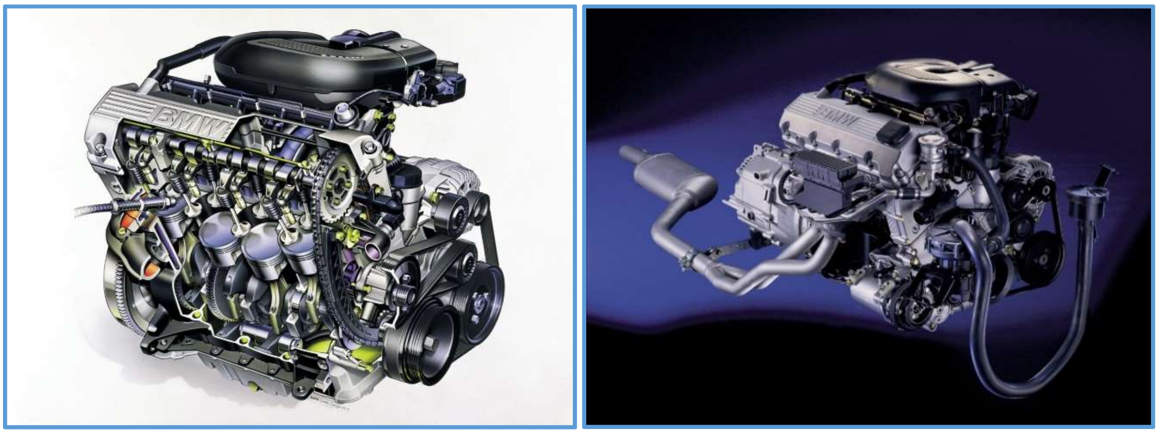


Figure 4.1 – BMW M43 engine

The BMW N42 is a straight-4 DOHC piston engine which replaced the M43 and was produced from 2001-2007.

Compared with its M43 predecessor, the N42 features a *DOHC valvetrain and variable valve timing* (called VANOS by BMW) and *variable valve lift* (called valvetronic by BMW).

Models					
Engine	Displacement	Power	Torque	Redline	Year
N42B18	1,796 cc	85 kW(116 PS; 114 hp)@ 5500	175 N·m(129 lb·ft)@ 3750	6500	2001-2004
N42B20	1,995 cc	105 kW(143 PS;141 hp)@6000	200 N·m(148 lb·ft)@ 3750	6500	2001-2004

Table 4.2 – BMW N42 models

N42B18

The N42B18 has a displacement of 1796 cc, uses Bosch DME ME9.2 fuel injection and has twin-balancing shafts.

The N42B18 won the 1.4-1.8 L category of the International Engine of the Year competition for 2001.

N42B20

The N42B20 has a displacement of 1995 cc, uses Bosch DME ME9.2 fuel injection and has twin-balancing shafts.

The BMW N45 is a straight-4 DOHC piston engine which replaced the BMW N42 and was produced from 2004-2011.

Compared with its N42 predecessor, the N45 does not have valvetronic variable valve lift. As the N42, the N45 has variable valve timing (called VANOS by BMW). The N45 was sold alongside the N43 (which has direct injection) and the N46 (which has valvetronic) straight-4 engines.

Year	1995-2000	2001-2003	2004-2008
Engine Reference	M43	N40/N42	N43/N45/N46
Technology	Dual-path intake manifold Knock sensing. Multipoint Fuel Injection Catalyst EGR	Variable Valve Timing Variable Valve Lift	Direct Injection Gasoline (N43)

Figure 4.2 – BMW M40 engine block evolution

So you can see how the manufacturer BMW introduced some of the systems mentioned in the previous chapter, as port deactivation, several multipoint injection systems, direct injection, VVT and VVL. By the variety of models of the same block, and distributed at the same time, it can be inferred that the introduction of new technology involves a risk not only for reliability but also higher costs of production to be not extended.

5 PSA XU ENGINE EVOLUTION

The XU engine type appeared in 1981 for the restyling of the Peugeot 305. The engine capacity of 1580cc XU goes to 1998 cc for petrol engines.

It is a four-cylinder engine OHC transversely mounted with a 30° rearward inclination.

The gearbox is also mounted transversely in the motor shaft, on the left thereof. The differential is part of the box and drives the front wheels via shafts.

The engine has four wet liners, a crankshaft bearing and five overhead cam head.

The camshaft and the water pump are driven by a toothed belt whose tension is adjusted by a spring roller. The camshaft directly command bucket tappets, the set being controlled by wedges mounted between the tappet and the valve stem. The igniter is controlled directly by the rear end of the camshaft.

The oil pump housed in the oil pan is controlled by chain, by the crankshaft. Lubrication is done under pressure. The oil pump is fed into the filter and then in the lubricating gallery, crankshaft and camshaft. The valve stems are lubricated by the oil falling to the camshaft in the oil pan. The chain and the oil pump gears are lubricated by crankcase oil.[19]

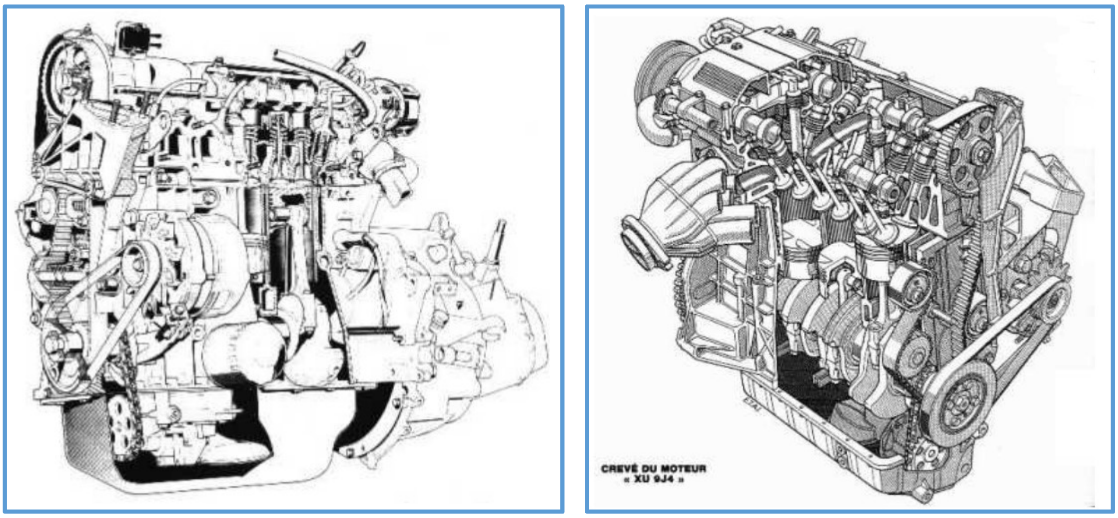


Figure 5.1 – PSA XU Engines

The engine name gives different information: displacement, charging or turbocharging and distribution. The first letters are XU, followed by a number, sometimes two, for the engine, and a sequence of letters or numbers for charging system (e, C – carburettor).

The **XU5** had a displacement of 1.6 L (1580 cc), with a bore of 83 mm and a stroke of 73 mm. All XU5 engines were SOHC 2-valve per cylinder designs. It used either a single or double-barrel carburettor or fuel injection, depending on model. Output ranged from 80–115 PS (79–113 hp/59–85 kW).

The **XU7** had a displacement of 1.8 L (1761 cc), with a bore of 83 mm and a stroke of 81.4 mm. All XU7 engines used fuel injection, with a 16-valve DOHC version, the XU7 JP4, also produced. Output ranged from 90–112 PS (89–110 hp/66–82 kW).

The **XU8** had a displacement of 1.8 L (1,775 cc), with a bore of 83 mm and a stroke of 82 mm. A single motor was produced in a few slightly different versions, the 16-valve DOHC turbocharged XU8 T, which was fitted to the 205 Turbo 16.

The **XU9** had a displacement of 1.9 L (1905 cc), with a bore of 83 mm and a stroke of 88 mm. Many versions were produced, from a double-barrel carburetted 8-valve to a 16-valve DOHC fuel injected model. Output ranged from 105–160 PS (104–158 hp/77–118 kW).

The **XU10** had a displacement of 2.0 L (1998 cc), with a bore and stroke of 86 mm. Many versions were produced, from a double-barrel carburetted 8-valve to a 16-valve DOHC fuel injected turbocharged model. Output ranged from 115–200 PS (113–197 hp/84–147 kW).

Models – PSA XU engines				
Engine	Bore and stroke	Displacement	Power	Technology
XU5 1C	83.0 x 73.0 mm	1580 cm3	80 hp	Carburettor (single barrel)
XU5 M3/Z	83.0 x 73.0 mm	1580 cm3	89 hp	Injection, catalyst
XU5 2C	83.0 x 73.0 mm	1580 cm3	92 hp	Carburettor (double-barrel)
XU5 J	83.0 x 73.0 mm	1580 cm3	105 hp	Injection
XU5 JA/K	83.0 x 73.0 mm	1580 cm3	115 hp	Injection
XU7 JB	83.0 x 81.4 mm	1761 cm3	90 hp	Injection, catalyst
XU7 JP	83.0 x 81.4 mm	1761 cm3	103 hp	Injection, catalyst
XU7 JP4	83.0 x 81.4 mm	1761 cm3	112 hp	16 valves, catalyst
XU8 T	83.0 x 82.0 mm	1775 cm3	200 hp	16 valves, turbo.
XU9 2C	83.0 x 88.0 mm	1905 cm3	105 hp	Carburettor (double-barrel)
XU9 J1/Z	83.0 x 88.0 mm	1905 cm3	105 hp	Injection, catalyst
XU9 2C	83.0 x 88.0 mm	1905 cm3	110 hp	Carburettor (double-barrel)
XU9 JA/Z	83.0 x 88.0 mm	1905 cm3	122 hp	Injection, catalyst
XU9 J2	83.0 x 88.0 mm	1905 cm3	125 hp	Injection
XU9 4C ?	83.0 x 88.0 mm	1905 cm3	126 hp	2 carburettors (double-barrel)
XU9 JA/K	83.0 x 88.0 mm	1905 cm3	130 hp	Injection
XU9 J4/Z	83.0 x 88.0 mm	1905 cm3	148 hp	16 valves, cat.
XU9 J4	83.0 x 88.0 mm	1905 cm3	160 hp	Injection, 16 valves
XU10 2C	86.0 x 86.0 mm	1998 cm3	115 hp	Carburettor (double-barrel)
XU10 J2C	86.0 x 86.0 mm	1998 cm3	123 hp	Injection, catalyst
XU10 M	86.0 x 86.0 mm	1998 cm3	130 hp	Injection
XU10 J4R	86.0 x 86.0 mm	1998 cm3	135 hp	16 valves, cat.

Models – PSA XU engines				
Engine	Bore and stroke	Displacement	Power	Technology
XU10 J2TE	86.0 x 86.0 mm	1998 cm3	145 hp	turbo, catalyst
XU10 J2TE	86.0 x 86.0 mm	1998 cm3	150 hp	turbo, catalyst
XU10 J4D/Z	86.0 x 86.0 mm	1998 cm3	150 hp	16 valves, catalyst
XU10 J4RS	86.0 x 86.0 mm	1998 cm3	167 hp	16 valves, catalyst
XU10 J4TE	86.0 x 86.0 mm	1998 cm3	200 hp	16 valves, turbo, cat.

Table 5.1 – PSA XU models

After 1998, the XU family was replaced by EW using many parts from the XU, most notably the crankshaft, but is built with lighter materials.

All EWs are DOHC multivalve with displacement from 1749 to 2231 cc. They are mainly used for large family cars and executive cars, as well as large MPVs, although the 2.0 L is also used for some hot hatch models.

The **EW7** has a bore of 82.7 mm and a stroke of 81.4 mm, for a displacement of 1749 cc. It is used as an entry level engine for the Citroën C5, the Peugeot 406 and the Peugeot 407.

The **EW10** has a bore of 85 mm and a stroke of 88 mm, for a displacement of 1997 cc. It is used widely throughout the PSA Group, including the Citroën C4 and C5 and Peugeot 206, 307 and 407. A gasoline direct injection variant, called EW10 D and marketed as **HPi**, was briefly used in the Citroën C5 and Peugeot 406 starting in 2001, but was discontinued in 2003 due to low sales. The EW10 J4S variant is a high performance version used in the 206 GTI 180, 206 RC, 307 Féline and C4 VTS. Power was raised to 177 hp (130 kW), although the two French brands round it up to 180 hp in advertising. EW10 A is a further development of the EW10 J4, presenting somewhat higher power and torque due to the introduction of Variable Valve Timing (VVT). Fuel consumption is also decreased. Power is 103 kW at 6000 rpm and torque 200 N·m at 4000 rpm. Citroen usually states 143 PS and Peugeot 140 PS for the same 103 kW engine. For most use, they are replaced with Prince engines.

The **EW12** was introduced to replace the low-pressure turbo variant of the XU10. It has a bore of 86 mm and stroke of 96 mm, for a displacement of 2231 cc. Citroën only uses it on the C8 MPV, while Peugeot, which has more a sporty image, uses it in the 406 SRi and 406 Coupe, 407, the 607 executive model and 807 MPV.

The **EW7A, EW10, EW12J4** were only, and no longer for sale in Europe as of January 1, 2011.

Model	Output	Notes	Year
EW7 J4	117 PS (115 hp/86 kW)	16-valve catalyst	1998-2011
EW7 A	125 PS (123 hp/92 kW)	16-valve catalyst	
EW10 D	140 PS (138 hp/103 kW)	gasoline direct injection catalyst	
EW10 J4 (RFN)	136 PS (134 hp/100 kW)	16-valve catalyst	
EW10 J4 (RFR)	135 PS (133 hp/99 kW)	16-valve catalyst	
EW10 J4S (RFK)	177 PS (174 hp/130 kW)	16-valve VVT catalyst	
EW10 A (RFJ)	140 PS (138 hp/103 kW)	16-valve VVT catalyst	
EW12 J4	158-163 PS (156-161 hp/116-120 kW)	16-valve catalyst	

The Prince family shares its basic block dimensions with the previous PSA TU engine family, but with bore and stroke measurements identical to the Tritec engine family. Some of the engineering was provided by BMW, including their Valvetronic variable valve lift system on the intake side. Other features include on-demand oil and water pumps. Gasoline direct injection with a twin-scroll turbocharger will be optional.

All Prince engines will share 84 mm (3.3 in) cylinder spacing and a 77 mm (3 in) bore. The engine features a two-piece "bedplate" aluminum crankcase for extra stiffness.

The development of new systems is a very expensive process and some manufactures like PSA took the option of a joint venture, in this case with BMW, to share resources, knowledge and technology.

6 Conclusion

This work shows how the mixture formation, combustion and exhaust gas after-treatment in gasoline engines have evolved in parallel with the implementation of the Euro standards, in particular during the period between Euro3 and Euro5.

Mixture formation (intake, injection, components geometry) to after-treatment exhaust gas systems have been redesigned and improved.

As standards become more strict, systems become more complex and must work together to get the required result. After treatment systems require an accurate control on mixture formation and combustion to be feasible their functionality. All these set of elements working together, could not exist without the electronic control. Increasingly engine components are sensorized to promote the interconnection of systems. The more control is needed, the more electronics must be implemented.

The complexity of current engines is such, that they cannot be correctly operated without the electronic control modules.

The possible way to continue meeting the standard´s driving cycles and avoid technological SI engine ceiling is hybridization with electric powertrains. But this technology will have to reduce its weight, cost and complexity, to be profitable for manufacturers, and come to stage.

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