

Importance of fuel injection system for low emissions, combustion noise and low fuel consumption

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Abstract. Due to increasingly stringent global regulations on engine and noise emissions, the fuel injection system plays a key role in reaching the stricter limits. The performance, low level of emissions and noise of a diesel engine is directly influenced by the fuel injection system which the main purpose is to deliver fuel at high pressure into engine's cylinders. Another aspect of a diesel engine is that it generates much more noise compared to a gasoline one. For this problem, the appropriate fuel injection system, such as a common-rail system, has made it possible to reduce combustion noise. The strategy consists in the use of a split injection into the combustion chamber by splitting the main injection. The purpose of this paper is to emphasize the difference between servo-controlled electrohydraulic injectors and direct acting (piezoelectric) injectors of the common-rail injection system and to explain how they can support the engine in achieving stricter emissions and noise regulations.

1. Introduction

More and more stringent emission levels and noise regulations are forcing car manufacturers, fuel injection system suppliers to develop new strategies to reduce the level of pollutant emissions and noise coming from the internal combustion engine without compromising the actual performance and fuel economy.

Figure 1 shows the worldwide emissions regulations [1], where each car manufactured according to a specific implementation timetable must comply with the limits set for that year. The paper also provides a summary of European Regulations on pollutant emissions and noise levels for passenger cars and light commercial vehicles. For example in Europe, the transport sector is among the first contributor to pollutant emissions released into the atmosphere, like CO, PM and NO_x.

Since 2000 year, in the road transport sector, the level of pollutant emissions has been considerably reduced by more than 25%, but for the non-road transport sector, such as agriculture, the level of emissions has remained constant over the years [2].

On the other hand, the number of vehicles is increasing very rapidly from one year to another, which means that the emissions regulations need to be updated more often in order to not lose out of control pollutant emissions released into the atmosphere.

To achieve the required limits, appropriate equipment types are needed. In the past, to meet Euro 4 and 5 standards, the fuel injection systems were not as performant as they are today, and a system such as Exhaust Gas Recirculation (EGR) has been used to meet the limits. For some engines to meet Euro 6 standard, it was added Selective Catalytic Reduction (SCR), which is an exhaust gas after-treatment system.



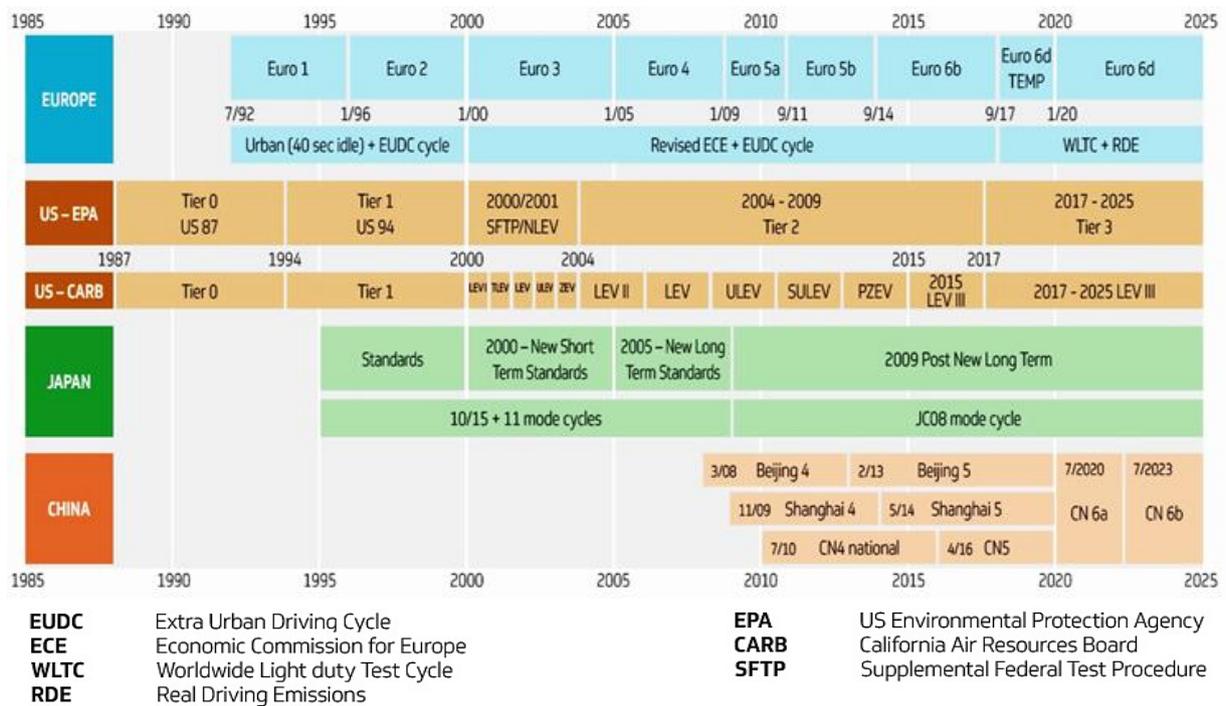


Figure 1. Worldwide emissions regulations / Implementation calendar [1].

The purpose of developing EGR and SCR systems was to reduce NOx emissions. For particle matter reduction, a diesel particulate filter (DPF) can be used as well, and for NOx and CO emissions a fuel injection system that can accurately control the amount of fuel injected into the combustion chamber.

In addition, the fuel injection system must be able to perform multiple injections to reduce combustion noise and to facilitate different forms of advanced combustion (low temperature, premixed or partially-premixed) to achieve very low NOx and soot formation for partial load conditions [3].

In order to get more injections into the combustion chamber, the common-rail system must be able to carry very high pressures and, secondly, proper coding of the electronic control unit (ECU) is required to precisely control the injectors. Injectors are one of the most important components of the common-rail system; they directly influence the burning process inside the combustion chamber and therefore the level of pollutant emissions is also affected.

Essentially, the purpose of our paper is to provide an analysis of the differences between servo-controlled electrohydraulic (solenoid) injectors and direct acting (piezoelectric) injectors and how it can improve the diesel engine performance, the level of emissions and the emitted noise.

2. Environmental and noise pollution standards for each vehicle category

Due to a multitude of categories of vehicles used in the transport sector, a single limit for this cannot be implemented, as there are vehicles with a different purpose.

Table 1 shows the vehicle category based on the Gross Vehicle Weight (GVW) and vehicle destination.

Table 2 sets out the emission limits to be complied with in accordance with the applicable standard of that year.

Table 1. Vehicle Categories [4].

Category	Description	Subcategory	Number of persons	Mass limit
M	Carriage of passengers, min 4 wheels, PC	M1	Up to 9	N/A
		M2	>9	$GVW \leq 5000$ kg
		M3		$GVW \geq 5000$ kg
		N1 CL1		Ref. M ≤ 1350 kg
N	Carriage of goods, min 4 wheels, LCV	N1 CL2		$GVW \leq 3500$ kg 1305 kg < Ref. M ≤ 1760 kg
		N1CL3	N/A	1760 kg < Ref. M ≤ 3500 kg
		N2		3500 kg < $GVW \leq 12.000$ kg
		N3		$GVW > 12.000$ kg

Table 2. Euro 5 and 6 Standards - Emissions limits [5].

Emissions	Unit	Euro Standards - Compression ignition emissions limits		
		Euro 5a	Euro 5b/b+	Euro 6b, 6c, 6d-Temp, 6d
PC M, LCV N1 CL1				
NO_x	mg/km	180	180	80
HC+NO_x		230	230	170
CO		500	500	500
PM		5.0	4.5	4.5
PN	Nb/km	-	6×10^{11}	6×10^{11}
LCV N1 CL2				
NO_x	mg/km	235	235	105
HC+NO_x		295	295	195
CO		630	630	630
PM		5.0	5.0	4.5
PN	Nb/km	-	6×10^{11}	6×10^{11}
LCV N1 CL3, N2				
NO_x	mg/km	280	280	125
HC+NO_x		350	350	215
CO		740	740	740
PM		5.0	5.0	4.5
PN	Nb/km	-	6×10^{11}	6×10^{11}

According to World Health Organisation (WHO), noise pollution is the second dangerous phenomenon influencing the environment, after the air pollution [6]. The main source of environmental noise is the transportation noise which is pulled up by always increasing needs for goods, energy, and personal transportation [7].

Table 3 and table 4 are showing European Regulations regarding the admissible noise levels generated by vehicles with the effective dates in three stages, until 2026.

Table 3. European sound level limits of motor vehicles for carriage of passengers [8].

Vehicle Category	Description of vehicle category	Limit values expressed in dB (A)		
		Phase 1 applicable for new vehicle types from 1 July 2016	Phase 2 applicable for new vehicle type from 1 July 2020 and for first registration from 1 July 2022	Phase 3 applicable for new vehicle type from 1 July 2024 and for first registration from 1 July 2026
M - Vehicles used for the carriage of passengers				
M_1	Power to mass ratio ≤ 120 kW/1000 kg	72	70	68
M_1	120 kW/1 000 kg < Power to mass ratio ≤ 160 kW/1000 kg	73	71	69
M_1	160 kW/1 000 kg < Power to mass ratio	75	73	71
M_1	Power to mass ratio > 200 kW/1000 kg number of seats ≤ 4 R point of driver seat ≤ 450 mm from the ground	75	74	72
M_2	Mass ≤ 2 500 kg	72	70	69
M_2	2500 kg < Mass ≤ 3 500 kg	74	72	71
M_2	3500 kg < Mass ≤ 5 000 kg; Rated engine power ≤ 135 kW	75	73	72
M_2	3500 kg < Mass ≤ 5 000 kg; Rated engine power > 135 kW	75	74	72
M_3	Rated engine power ≤ 150 kW	76	74	73
M_3	150 kW < Rated engine power ≤ 250 kW	78	77	76
M_3	Rated engine power > 250 kW	80	78	77

Table 4. European sound level limits of motor vehicles for carriage of goods [8].

Vehicle Category	Description of vehicle category	Limit values expressed in dB (A)		
		Phase 1 applicable for new vehicle types from 1 July 2016	Phase 2 applicable for new vehicle type from 1 July 2020 and for first registration from 1 July 2022	Phase 3 applicable for new vehicle type from 1 July 2024 and for first registration from 1 July 2026
N - Vehicles used for the carriage of goods				
N_1	$Mass \leq 2\,500\text{ kg}$	72	71	69
N_1	$2\,500\text{ kg} < Mass \leq 3\,500\text{ kg}$	74	73	71
N_2	$Rated\ engine\ power \leq 135\text{ kW}$	77	75	74
N_2	$Rated\ engine\ power > 135\text{ kW}$	78	76	75
N_3	$Rated\ engine\ power \leq 150\text{ kW}$	79	77	76
N_3	$150\text{ kW} < Rated\ engine\ power \leq 250\text{ kW}$	81	79	77
N_3	$Rated\ engine\ power > 250\text{ kW}$	82	81	79

The studies revealed that people who are regularly exposed to consistent high sound levels they are more prone to hearing disorders, hypertension, ischemic heart disease, discomfort and sleep disturbances.

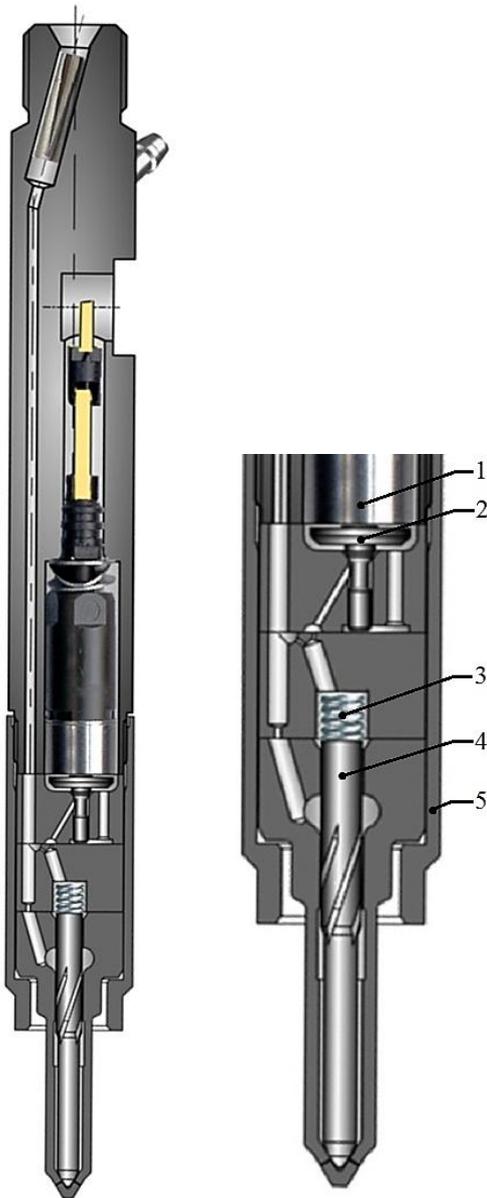
3. Design differences between servo-controlled electrohydraulic (solenoid) and direct acting (piezoelectric) injectors

The design and working principle of servo-controlled electrohydraulic (solenoid) and direct acting (piezoelectric) injectors are totally different.

For the solenoid injector, the operating principle consists of using a servo-hydraulic concept to control the needle movement, such as the actuation of the Solenoid 1 and opening of the Control Valve 2 (figure 2). Then, the pressure is released from the control chamber through an orifice which creates a hydraulic imbalance and leads to needle lifting from the nozzle seat.

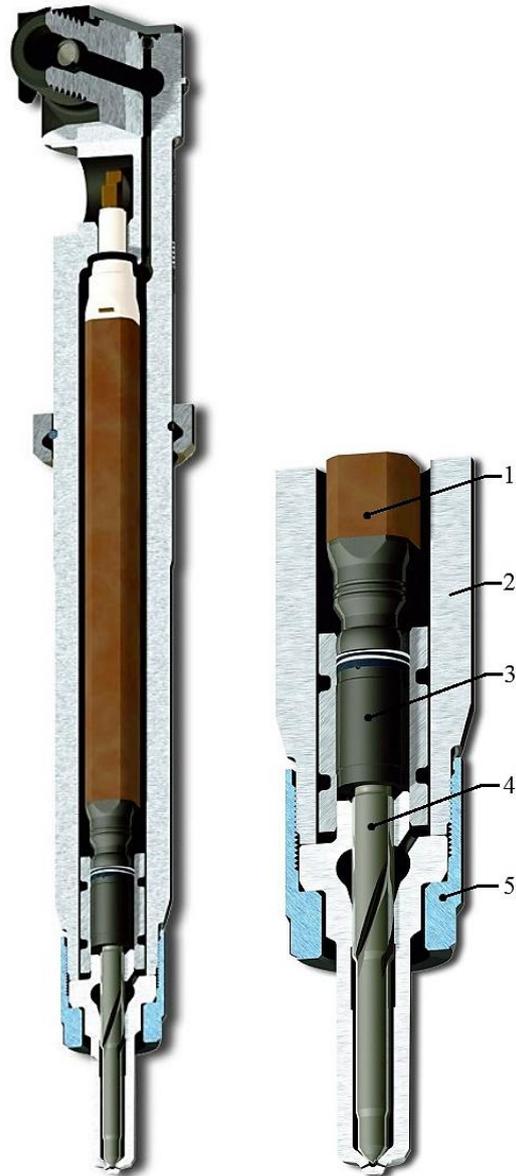
Also, consideration should be given to the opening time of the injector, where servo-controlled electrohydraulic injector (solenoid) depends on the rail pressure and the negative pressure on the return circuit created by the high-pressure pump on the fuel return circuit to the tank. Due to a multitude of factors that influence the opening and closing time of the injector, a ramp shape of injection under all system pressure conditions is generated and this shape tends to approach a square shape as the system pressure increases.

On the other hand, the opening and closing of the direct acting (piezoelectric) injector is controlled by actuating the Piezoelectric Stack 1 and the Needle Movement Amplifier 3 which acts directly on the injector Needle 4 and lifts up the needle from the nozzle seat (figure 3).



1-Solenoid; 2-Control Valve;
3-Helicoidal Spring; 4-Needle;
5-Capnut;

Figure 2. Servo-controlled electrohydraulic injector (Solenoid) [9].



1-Piezoelectric Stack; 2-Injector Body;
3-Needle Motion Amplifier; 4-Needle;
5-Capnut;

Figure 3. Direct acting injector (Piezoelectric) [10].

Compared to the servo-controlled electrohydraulic (solenoid) injector, the direct acting (piezoelectric) doesn't have a return circuit and the opening and closing times do not depend on the rail pressure, which is a significant advantage, as the rail pressure is not constant during engine operation and varies depending on the engine load.

The visible difference can be seen in figure 5 where the direct acting (piezoelectric) has a square shape injection at all system pressure conditions compared to the servo-controlled electrohydraulic (solenoid) injector of figure 4 which has a ramp shape injection under all system pressure conditions.

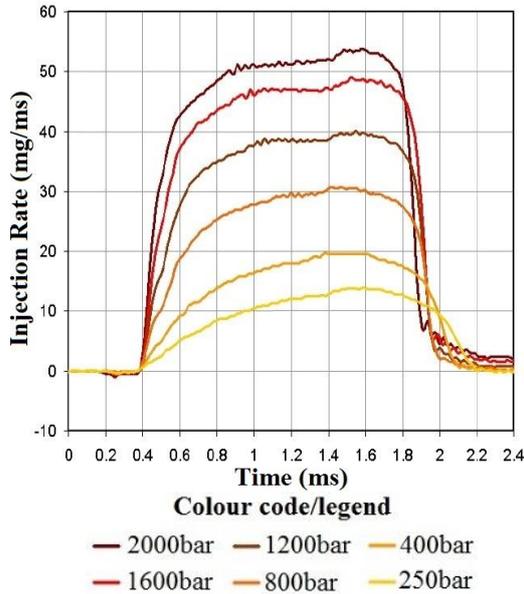


Figure 4. Injection rate diagram at different rail pressures for the servo-controlled electrohydraulic injector (Solenoid) [10].

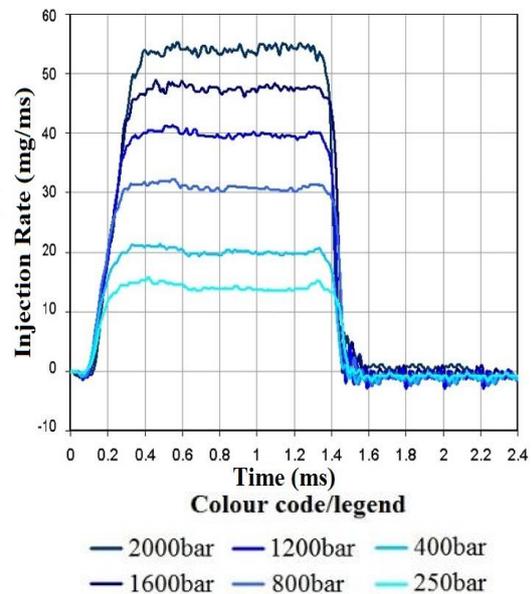


Figure 5. Injection rate diagram at different rail pressures for the direct acting injector (Piezoelectric) [10].

Figure 6 describes the injection pattern of the servo-controlled electrohydraulic injector (solenoid) and figure 7 presents the injection pattern for the direct acting injector (piezoelectric) at 220 μ s after the start of the injection.

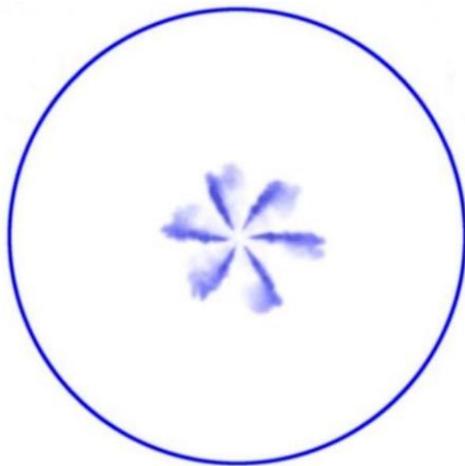


Figure 6. Injection pattern for servo-controlled electrohydraulic injector at 220 μ s after the start of injection (Solenoid) [10].

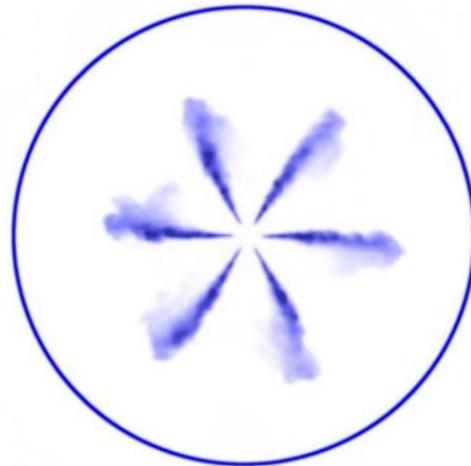


Figure 7. Injection pattern for direct acting injector at 220 μ s after the start of injection (Piezoelectric) [10].

From a visual point of view, it can be seen that the direct acting (piezoelectric) injector introduces much more fuel into the cylinder, which means that it better controls the total amount of fuel injected

and further conducts to a better control of the air-fuel mixture and resulting in reduced pollutant emissions released to the atmosphere.

4. Divided injection

The split injection has emerged as a necessity for the development of direct injection systems due to the combustion noise produced and the emissions generated by single main fuel injection. Figure 8 shows an example of divided injection from a diesel engine with five injections per cycle.

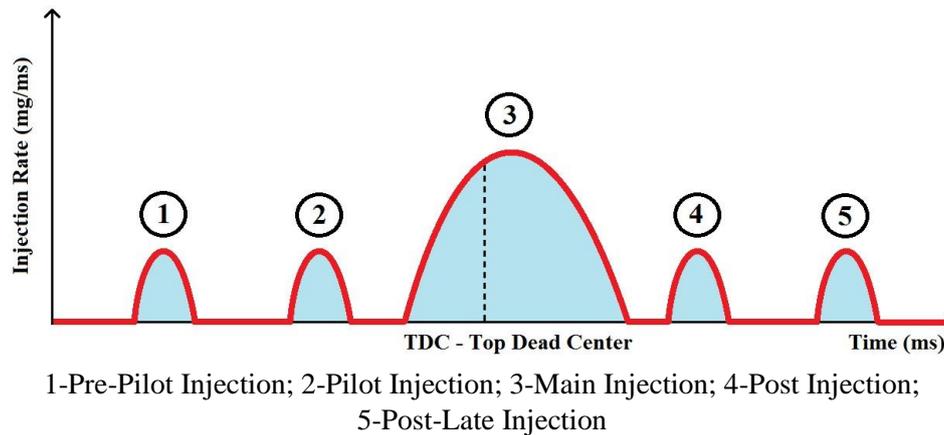


Figure 8. Example of divided injection for diesel engines.

Below are summarised the characteristics and advantages of each split injection sequence:

- *Pre-Pilot:*
 - Is carried out with an advance of $120\div 90^\circ$ to TDC;
 - The amount of fuel injected is around $1\div 4 \text{ mm}^3$;
 - Controls the pressure variation in the cylinder;
 - Reduces combustion noise;
 - Improves the cold start of the engine;
 - Increases engine torque at reduced speeds.
- *Pilot:*
 - Controls combustion noise;
 - Reduces particle formation, NO_x and HC.
- *Main:*
 - Makes the requested engine torque.
- *Post:*
 - Reduces particulate emissions by extending the combustion process.
- *Post-Late:*
 - Regenerates the particulate filter.

5. Conclusions

In the future, to meet the new regulations, the diesel engines will certainly be equipped with a common-rail system with direct acting (piezoelectric) injectors.

As an advantage of the direct acting (piezoelectric) injectors in addition to those servo-controlled electrohydraulic (solenoid) ones, it can be mentioned a three times faster opening and closing of the nozzle needle independent of rail pressure at a speed of 3 m/s which leads to a square injection shape at any rail pressure [10]. Considering that the fuel spraying is improved and the control of the total amount of fuel injected into engine's cylinders is more accurate than the servo-controlled electrohydraulic (solenoid) injectors, the pollutant emissions such as nitrogen oxides and particulate

are reduced by 30%. In the same time, the torque and the engine power are increased by 10%, as well the noise level and the fuel consumption are improved due to precise multiple injections per cycle.

The performances of the direct acting (piezoelectric) injectors compared to the servo-controlled electrohydraulic (solenoid) injectors were presented in this paper, and it is clear that the piezoelectric has the key characteristics to create a clean combustion process inside the combustion chamber.

6. References

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