

# Comparative Assessment of CI Engine Response

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**Abstract** The response of the piston internal combustion engine provides an important indicator to assess the engine ability to adapt to constantly varying load conditions in its operation. It is the main criterion by which engines powering automotive vehicles are evaluated. It also affects road safety. The engine response depends on the profile of the curve that shows changes in the engine torque as a function of the crankshaft rotational speed. The paper presents a comparison of CI engines representing different generations with respect to constructional level. The engines that underwent comparison were equipped with the fuel system with a rotary injection pump and with Common Rail fuel system.

**Keywords** CI internal combustion engine, engine response, engine response assessment indicators, engine response modification, engine dynamics

**JEL** L99

## 1. Introduction

To power an automotive vehicle, a high-speed rotation, piston, internal combustion engine is necessary. It needs to dynamically respond to changing traffic conditions and to carry out fast manoeuvres, thus improving the economy and road safety. The first compression-ignition engines were low-speed rotation and they were, therefore, used in industries. Advancements in those engines, however, made it possible to employ them in trucks. Development of piston compression ignition engines was limited because it was not possible to increase the rotational speed. That resulted from a fairly large angle of rotation of the crankshaft that corresponded to the fuel auto-ignition delay. Long auto-ignition delay causes hard engine operation and considerable mechanical stress impact. CI engines had large weight and were noisy in operation. They were characterised by lower power extracted from piston displacement. As a result, their applicability to small passenger cars was very limited. The improvement was sought by shortening the auto-ignition delay and by modifying the profile of torque changes as a function of the crankshaft rotational speed. The use of classical multi-section injection pumps or rotary pumps did not make it possible to obtain high injection pressures. Improvements in the fuelling system due to the use of unit injector systems and Common Rail fuel systems with a high-pressure pump and electronically controlled injectors allowed the elimination of the drawbacks of CI engines.

Modern CI engines are much lighter, less noisy and, above all, they make it possible to obtain performance (power and torque) comparable with modern spark-ignition engines, at lower fuel consumption. These advantages resulted in increased interest in these engines with respect to their application to passenger cars, also the smallest ones [1]. Currently, CI engines with small piston displacement, which reach maximum crankshaft rotational speeds even above 5000 rpm, are commonly used in passenger cars.

## 2. Modern CI Engines

Presently used piston IC engines must be able to generate as small harmful environmental effects as possible, which means they need to produce low exhaust toxicity and noise. They have to consume little fuel, and to be characterised by response that allows dynamic driving under traffic conditions presently prevailing on the roads. Requirements posed for internal combustion engines make it necessary to search for different technical solutions to reduce exhaust emissions, fuel consumption and to improve engine traction properties [2, 3]. As regards CI engines, the most widely used technical solutions mentioned above include the following [4-11]:

- common use of direct fuel injection,
- the use of modern fuel systems producing high injection pressures, i.e. Common Rail systems or unit injector systems,
- the use of multi-valve timing gear system with controlled parameters of valve operation,
- the use of controlled supercharging systems with the charge-air cooling,
- the use of electronically controlled exhaust gas recirculation (EGR) systems with re-circulated exhaust cooling,

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- electronic control of injection,
- the use of multi-stage fuel injection,
- shaping of the combustion space geometry,
- the control of the working medium swirl and turbulence,
- the use of devices purifying the exhaust gas,
- the use of onboard diagnostic systems,
- the use of the cooling systems with a higher coolant temperature and faster engine warm-up time from the start-up,
- control that makes possible to optimise the process of combustion heat release by means of using high pressure injection, and also the fuel injection pattern modification in time.

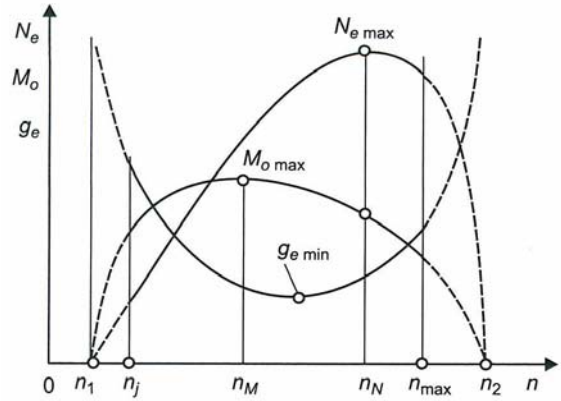
### 3. Response of the Piston Internal Combustion Engine

If it were possible to ensure constant engine power as a function of the crankshaft rotational speed, the gearbox would not be necessary. Then, the engine would generate sufficient driving force on the wheels that would be able to overcome motion resistance. In fact, that is not possible because the processes occurring in the engine and its systems, and thus the engine power, depend on the crankshaft rotational speed. The efficiency of the processes in the engine is also varied because it depends on the conditions of the engine operation [12]. Those factors make the engine power vary with the crankshaft rotational speed. The ability of the engine to respond to changing conditions of operation was termed engine response. It is of vital importance for engines used to power automotive vehicles.

The response of an internal combustion engine involves its adaptability to changes in loads and rotational speeds [13]. With respect to piston internal combustion engines used to power automotive vehicles, the engine response provides an important indicator for the assessment of engine in-service performance. The notion of the response index was introduced to evaluate the engine response. The engine response index is expressed as the product of the torque response index  $e_M$  and the rotational speed response index  $e_n$ :

$$e = e_M \cdot e_n \quad (1)$$

Indexes  $e_M$  and  $e_n$  provide an assessment of the pattern of changes in the effective power  $N_e$  and torque  $M_o$  as a function of the crankshaft rotational speed when the engine operates under full load characteristics. That is equivalent to the settings of the fuelling system controls which ensure obtaining the maximum effective power every time. The pattern of effective power  $N_e$  and torque  $M_o$  as a function of the crankshaft rotational speed, for the engine operating under full load characteristics, with the denoted parameters necessary to calculate the response indexes is shown in Fig. 1.



**Figure 1.** Engine full load characteristics with superimposed parameters necessary to calculate the engine response:  $n_1$  – rotational speed at the engine start-up,  $n_j$  – idle speed,  $M_{o\max}$  – maximum torque,  $N_{e\max}$  – maximum effective power,  $g_{e\min}$  – minimal specific fuel consumption,  $n_M$  – rotational speed at the maximum torque,  $n_N$  – rotational speed at the maximum power,  $n_{\max}$  – maximum permissible rotational speed,  $n_2$  – rotational speed at which the engine generated power is equal to zero

The index of the torque response  $e_M$  is determined as the quotient of the maximum torque  $M_{o\max}$  and the torque  $M_{oN}$  corresponding to the maximum power  $N_{e\max}$ :

$$e_M = \frac{M_{o\max}}{M_{oN}} \quad (2)$$

The index of the torque response  $e_M$  provides an assessment of the engine capacity to overcome load increase and it depends on the torque curve profile. A higher value of this index is obtained when the torque curve is steeper. That makes it easier for the engine to overcome an increasing external load without the necessity to change the transmission ratio in the power transmission system. The torque curve can be shaped by the proper construction of the intake and timing gear systems, the use of supercharging and fuel injection, improvement in the course of mixture combustion in the cylinder, and, in particular, electronic control of the amount of air and fuel delivered into the cylinders, and of the processes that occur in the cylinders.

The index of the rotational speed response  $e_n$  is given as a quotient of the crankshaft rotational speed  $n_N$ , corresponding to the maximum effective power  $N_{e\max}$ , and the engine crankshaft rotational speed  $n_M$ , corresponding to the maximum torque  $M_{o\max}$ :

$$e_n = \frac{n_N}{n_M} \quad (3)$$

The index of the engine rotational speed response  $e_n$  indicates in what range of the rotational speed, the engine will be able to adapt its operation to changing driving conditions, i.e. to the increasing load. A higher value of the index shows that the engine is better applicable to the traction uses. Such an engine has a greater range of rotational speed that can be used [14]. The driver will less often have to change gears. The index of the engine rotational speed response depends on the rotational speed span between that at the maximum torque  $n_M$  and that at the maximum power  $n_N$ . This indicator can be modified by shifting the values of the maximum torque into the lower rotational speeds. An increase in the

value of the index of the engine rotational speed response results in an increase in the engine response.

#### 4. Characteristics of the Selected CI Engines

For the analysis, IC internal combustion engines that represent different design generations were selected. One of those is medium-speed, naturally aspirated Perkins AD3.152 UR engine, with the fuel system containing the mechanically controlled rotary injection pump. It is three-cylinder CI engine with direct fuel injection into the combustion chamber located in the piston bottom. Injection is performed by mechanical injectors. This engine was used to power agricultural tractors and light vans.

The other engine, namely FIAT 1.3 MULTIJET SDE 90 KM, shows a modern design. The engine uses new technical solutions, which results in meeting current requirements. This is a high-speed, turbocharged engine with Common Rail fuel system. The engine is equipped with a turbocharger with variable geometry vanes. The fuel charge, injected into the cylinders under specified conditions of engine operation, is divided into three portions. Electronic control unit controls the cylinder filling with air and fuel injection. FIAT 1.3 MULTIJET SDE 90 KM engine is used to power small passenger cars.

In the paper, the indexes of response of two other CI engines were also presented. Those are produced by the same manufacturer and have similar basic design parameters, but they are equipped with different fuel systems. The first of those, namely Perkins 1104D-44TA engine is fitted with mechanically controlled fuel system with a rotary injection pump. The other, i.e. Perkins 1104D-E44TA engine, has electronically controlled Common Rail fuel system. Those engines are mostly used to power machinery. The basic specifications of the engines mentioned above are given in Table 1.

**Table 1.** Basic specifications of the engines: Perkins AD3.152 UR, FIAT 1.3 MULTIJET SDE 90 KM, Perkins 1104D-44TA, Perkins 1104D-E44TA

Parameter	AD3.152 UR	1.3 MULTI-JET	1104D-44TA	1104D-E44TA
Cylinder arrangement	in-line	in-line	in-line	in-line
Number of cylinders	3	4	4	4
Type of injection	direct	direct	direct	direct
Type of the fuel system	rotary injection pump	Common Rail	rotary injection pump	Common Rail
Engine maximum power; kW	34.6	66	75	106.2
Rotational speed at the maximum power; rpm	2000	4000	2200	2200
Engine maximum torque; Nm	165.4	200	416	556.0
Rotational speed at the maximum torque; rpm	1300 ÷ 1400	1750	1400	1400
Engine cubic capac-	2.502	1.251	4.4	4.4

ity; dm <sup>3</sup>				
Cylinder bore; mm	91.44	69.6	105	105
Piston stroke; mm	127	82	127	127
Compression ratio	16.5	17.6	18.2	16.2
Air supply system	naturally aspirated	turbocharger	turbocharger	turbocharger

#### 5. Response of the Selected CI Engines

On the basis of full load characteristics, response indexes were computed for the engines of concern. Those include the index of torque response, the index of rotational speed response and the index of the engine response. The values of the indexes are presented in Table 2.

**Table 2.** Values of indexes determined to assess the response of the engines: Perkins AD3.152 UR, FIAT 1.3 MULTIJET SDE 90 KM, Perkins 1104D-44TA, Perkins 1104D-E44TA

Index	AD3.152 UR	1.3 MULTI-JET	1104D-44TA	1104D-E44TA
Index of torque response	1.032	1.324	1.156	1.209
Index of rotational speed response	1.428	2.285	1.571	1.571
Index of engine response	1.474	3.027	1.816	1.899

The computation results show that the lowest values of response indexes are found for the Perkins AD3.152 UR engine, which is the oldest design in the four engines. It is a three-cylinder, naturally aspirated, mechanically controlled engine. In the four-cylinder Perkins 1104D-44TA engine, also mechanically controlled, turbocharging with the charge-air cooling is used. That allows a considerable increase in the engine response value. In the Perkins 1104D-E44TA engine, the electronically controlled Common Rail fuel system is used and the compression ratio is reduced when compared with Perkins 1104D-44TA. That makes it possible to clearly increase the maximum effective power and the torque, and to increase the torque response index, and to a small extent, the engine response index. The index of rotational speed response, however, is unaffected because the maximum values of the torque and effective power are obtained for the same values of the crankshaft rotational speed as it is the case for Perkins 1104D-44TA engine. To increase the engine response, it would be necessary to increase the span of rotational speeds between that at the maximum torque and that at the maximum effective power. This engine, however, is used to drive machinery, thus high value of the engine response is not required. FIAT 1.3 MULTIJET SDE 90 KM was specially designed to power small passenger cars, in which high dynamics in fast-flowing traffic is of major importance. All modern solutions were applied to this engine, due to which it was possible to significantly increase the crankshaft rotational speed. The maximum power is obtained at 4000 rpm. The torque curve, as a function of the rotational speed, is shaped by means of electronic control of the engine supercharging, and of the amount and course of the fuel injection into the cylinders. The engine response index exceeds the value of 3. This value

could be increased by reducing the rotational speed corresponding to the engine maximum torque.

## 6. Summary

The results of the tests on the response of selected internal combustion engines indicate that engines used to power passenger cars need to show highly dynamic characteristics in congested traffic. That is of major importance for, among others, traffic safety. Dynamic performance is ensured by high-response engines, i.e. those capable of adapting to variable loads. The application of supercharging, high pressure multi-stage fuel injection in Common Rail fuel systems and the electronic control of processes in the engine and its systems makes it possible to shape the pattern of torque changes as a function of the rotational speed. That allows improvement in the engine response and also makes it possible to meet the expectations of users.

The engine response is an indicator necessary to assess the engine dynamics. The engine response index provides an important instrument to evaluate the engine performance in service. A higher value of the index corresponds to better traction properties. Engine with high response allows drivers to accelerate, climb grades and overcome other loads in a more efficient way. Good dynamic characteristics of the internal combustion engine, expressed in the form of the engine response, should facilitate the dynamic performance of the vehicle powered by such engine. Engine response is of considerable importance in traffic fast flow and congestion. Poor engine response may adversely affect fluid traffic flow and pose a threat while performing overtaking manoeuvres.

When driving a car powered by high response engine, it is less often necessary to change gears. An increase in the engine load produces an increase in the fuel charge delivered to the engine cylinders. Appropriate torque reserve makes it possible to overcome motion resistance without the necessity to change the transmission ratio in the power transmission system. In overtakes, a higher response engine accelerates quicker because of the torque reserve, especially in higher gears. That makes it possible to perform overtaking manoeuvres faster, thus to prevent dangerous situations.

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