IMPACT OF SIMPLIFIED ELECTRONIC CYLINDER DEACTIVATION ON SPECIFIC FUEL CONSUMPTION OF SPARK-IGNITION ENGINE

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Abstract. The paper presents an experimental study of the effect of electronic cylinder deactivation on the fuel efficiency of a spark-ignition internal combustion engine. The object of the study was a four-cylinder naturally aspirated Toyota 4A-FE engine with a displacement of 1.6 liters, tested on an engine dynamometer. Cylinder deactivation was achieved by disconnecting the control pulses of the fuel injectors of two cylinders without changing the gas distribution phases (valve timing) and without disconnecting the ignition system in the deactivated cylinders. Experimental fuel consumption measurements were carried out at fixed values of engine speed and engine torque in the low and medium load range at a stoichiometric air-fuel ratio ($\lambda = 1$) and optimal ignition timing. The experimental results showed that electronic cylinder deactivation can reduce specific fuel consumption by up to 8.7% in a limited range of engine operating modes, while the effectiveness of the method is significantly reduced at high engine speeds. The results confirm the possibility of improving the fuel efficiency of gasoline engines using simplified cylinder deactivation schemes.

Keywords: electronic cylinder deactivation, spark ignition engine, fuel consumption, engine dynamometer, partial load.

Introduction

With stricter environmental requirements and the need to reduce operating costs, improving the fuel efficiency of gasoline internal combustion engines remains a pressing engineering challenge [1; 2]. Despite the active development of electrified power plants, naturally aspirated gasoline engines are still widely used in the mass segment of passenger cars, which makes it expedient to search for relatively simple and cost-effective ways to improve their efficiency [1-3].

One of the key reasons for increased fuel consumption in gasoline engines under real operating conditions is operation in low and medium load modes. In these modes, a significant portion of the indicator work is lost to overcome pumping losses caused by air flow throttling [4; 6]. As a result, the thermal efficiency of the engine decreases and the specific fuel consumption increases [4].

One well-known approach to reducing pumping losses is to deactivate some of the engine cylinders when operating at partial loads [7-9]. The principle of this technology is to temporarily disconnect individual cylinders from the working process, which allows the load to be redistributed to the remaining active cylinders, increasing the throttle opening and thereby reducing intake losses [6-8]. In serial power units, cylinder deactivation is usually implemented by means of complex mechanical and electrohydraulic systems that shut down the valve mechanism, fuel supply, and ignition. Such solutions require a significant complication of the engine design and, as a result, an increase in its cost [9-11].

At the same time, the effectiveness of simplified cylinder deactivation schemes, in which deactivation is carried out exclusively at the fuel supply level, without interfering with the gas distribution mechanism and ignition system, remains insufficiently studied [6; 12; 13]. From an engineering point of view, this approach is of practical interest because it allows cylinder deactivation to be implemented with minimal design changes to the engine and using existing electronic control systems. However, the lack of valve deactivation and the preservation of standard gas distribution phases can have a noticeable effect on gas exchange, process stability, and the final fuel efficiency, which requires experimental verification [6; 10; 12; 14].

Kapus et al. proposed a concept for electronic cylinder deactivation in four-cylinder engines based on fuel cut-off and camshaft timing optimization, noting that fuel consumption is reduced by 10% at 2000 rpm and 1 bar BMEP (Brake Mean Effective Pressure). Cylinder deactivation ceases to be effective as the load increases to 3 bars. However, these results were obtained primarily through simulation [5].

Ram et al. experimentally demonstrated that fuel savings in a three-cylinder engine at 3000 rpm increased with load, reaching up to 11.55% at higher part-load conditions, while remaining limited or negative at low loads, highlighting the need for further experimental studies of simplified deactivation systems [15].

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Most published studies in this field focus either on modeling cylinder deactivation processes or analyzing production engines with complex factory cylinder deactivation systems [7; 9; 11]. Experimental work in which the effect of deactivation is assessed based on direct fuel consumption measurements on an engine test bench for a naturally aspirated gasoline engine with simplified electronic implementation is limited in the literature [6; 12; 13]. In particular, there is insufficient data on the limits of applicability of this approach in terms of speed and load, as well as on the modes in which deactivation can lead to a decrease or, conversely, an increase in fuel consumption.

In this regard, the purpose of this work is to experimentally evaluate the effect of electronic cylinder deactivation on the fuel efficiency of a gasoline internal combustion engine under steady-state low- and medium-load conditions without changing the valve timing and ignition system.

The experimental results obtained in this work allow us to assess the real potential of simplified electronic cylinder deactivation, determine the areas of its effective application, and identify limitations associated with an increase in the engine speed and changes in the load regime. The results of the study may be of practical interest in the development of engine control software algorithms aimed at improving fuel efficiency without significantly complicating the design of the power unit.

Materials and methods

The research object was a four-cylinder naturally aspirated gasoline engine with spark ignition, Toyota 4A-FE, with displacement of 1.6 liters. This engine belongs to a family of mass-produced engines and features distributed fuel injection, a classic gas distribution system without phase regulators, and electronic control of the injection and ignition processes. The main technical characteristics of the engine are given in Table 1.

Table 1

Main parameters of the engine used in the experiment

Engine parameters	Units
Engine code	4A-FE
Power, P_e, kW	79
Torque, M_{mot}, N·m	136
Displacement, V_d, cm^3	1587
Firing order	1-3-4-2
Bore X stroke, mm	81x77
Compression ratio	9.5:1
Maximum engine speed, $n_{\max}$, rpm	6000

This is relatively common, has a simple design, and lacks standard gas distribution phase control systems, which allows for an objective assessment of the effect of cylinder deactivation without additional factors associated with adaptive gas exchange control systems.

During the experiment, cylinder deactivation was performed via electronic control by cutting off the control pulses to the fuel injectors of two engine cylinders (Nos. 2 and 3). The ignition system and the gas distribution mechanism remained unchanged, and the valves of the deactivated cylinders continued to operate in their normal phases. This approach allows the effect of fuel supply shutdown on fuel consumption and engine performance to be investigated without making mechanical changes to the power unit design. The experiment compared two engine operating modes:

- the base mode with all four cylinders operating,
- the mode with electronic deactivation of two cylinders while maintaining the same rpm and torque values.

Experimental fuel consumption measurements for two- and four-cylinder operation were performed fully warmed up, after running at idle for an extended period, the oil and coolant had reached their operating temperatures. The engine control unit (VEMS) was used to maintain a stoichiometric air–fuel ratio ($\lambda = 1$) and to adjust ignition timing to optimal values for each operating condition. The experiment was conducted on an engine dynamometer equipped with a water brake (Schenck U1 16h) that maintains the required engine torque at a fixed crankshaft speed. Torque was measured using a strain-gauge load cell installed on the dynamometer arm. The torque value was calculated based on the measured force and the known lever arm length. Fuel consumption was determined by directly measuring the volume (mass) of fuel consumed over a fixed period of time using a calibrated measuring flask (250 ml, resolution ± 20 ml) and a digital chronometer (resolution ± 0.1 s).

For each measurement, the crankshaft speed, developed torque, time of consumption of a given volume of fuel, as well as additional parameters necessary to control the stability of the engine operating mode were recorded. The experiments were conducted with the engine fully warmed up and under stable thermal conditions.

Measurements were taken in the crankshaft speed range from 1600 to 3500 rpm and the torque range from 10 to 30 N·m. Operating points at 5 and 40 N·m were extrapolated from the experimentally obtained data. This area corresponds to low and medium load modes. To increase the reliability of the results, each operating point was measured at least three times, and the final values of fuel consumption were obtained by averaging the measured data.

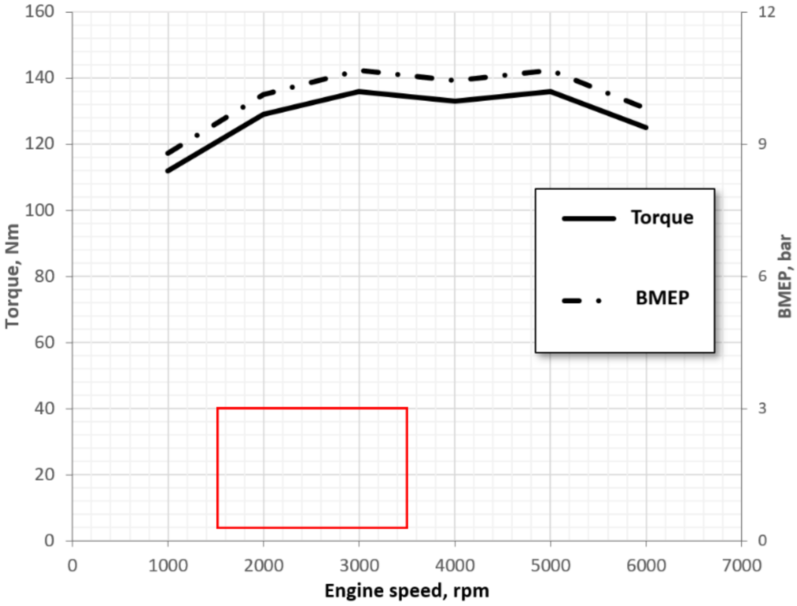

Fig. 1. **Engine map with fuel flow measurement area**

To plot the BMEP curve in proportion to the engine torque (N·m), the following formula was used:

$$BMEP = \frac{M_{mot} \cdot 2\pi}{i \cdot V_D}, \tag{1}$$

where $BMEP$ - brake mean effective pressure, bar;
M_{mot} – engine torque, N·m;
i – coefficient (4 stroke engines = 0.5);
V_D – engine displacement, m^3

To assess the impact of cylinder deactivation on fuel consumption, the relative difference in fuel consumption between modes with four and two active cylinders was calculated at the same engine speed and torque values. The data obtained were used to construct maps of relative changes in fuel consumption in the studied range of engine operating modes.

In addition, based on the experimental data, the specific effective fuel consumption was calculated, which made it possible to compare the change in engine fuel efficiency at different operating modes and identify the areas in which electronic cylinder deactivation provides the greatest effect.

Results and discussion

Experimental studies were aimed at quantitatively assessing the impact of electronic cylinder deactivation on the fuel consumption of a gasoline engine at fixed crankshaft speed and torque values.

A comparison was made between the base engine mode with four active cylinders and the mode with electronic deactivation of two cylinders.

Measurements were performed in the speed range from 1600 to 3500 rpm and loads from 10 to 30 N·m, which corresponds to the range of low and medium loads. For each mode, fuel consumption was recorded, after which the relative difference between the modes with four and two active cylinders was calculated.

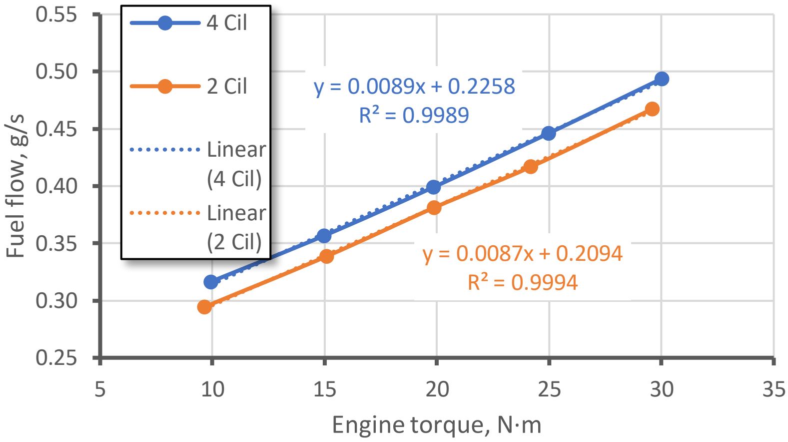

Fig. 2. **Example of fuel flow data analysis at 1600 rpm**

The fuel flow difference (FFD) was calculated using the following formula:

$$FFD = \frac{F_g(4cyl) - F_g(2cyl)}{F_g(4cyl)}, \tag{2}$$

where $F_g(4cyl)$ – fuel flow with four active cylinders, g·s^{-1};
$F_g(2cyl)$ – fuel flow with two active cylinders, g·s^{-1};
FFD – fuel flow difference between four- and two- cylinder operation, %.

At a crankshaft speed of 1600 rpm, deactivating two cylinders led to a steady reduction in fuel consumption across the entire load range studied. The relative reduction in fuel consumption ranged from 4.6% to 5.8% compared to the base engine operating mode. The main results obtained in this test mode are shown in Table 2.

Table 2

Fuel flow measurement results at 1600 rpm

Torque M_{mot}, N·m	**Fuel flow, g·s^{-1}**		**Difference, g·s^{-1}**	**Difference, %**
	4-cylinders	**2-cylinders**		
5	0.270	0.253	0.017	6.44
10	0.315	0.296	0.018	5.84
15	0.359	0.340	0.019	5.40
20	0.404	0.383	0.020	5.05
25	0.448	0.427	0.021	4.77
30	0.493	0.470	0.022	4.55
40	0.582	0.557	0.024	4.19

The observed reduction in fuel consumption under cylinder deactivation can be explained by a decrease in pumping losses. When part of the cylinders are deactivated, the load on the remaining active cylinders increases, which leads to a wider throttle opening at the same engine torque. As a result, the pressure drop across the throttle decreases, improving the gas exchange process and increasing the overall engine efficiency under partial load conditions.

The greatest effect was recorded at minimum loads (10 N·m), with the savings gradually decreasing as the torque increased. Nevertheless, at all points studied at this speed, cylinder deactivation provided a positive fuel-saving effect.

When the speed was increased to 2500 rpm, the effect of cylinder deactivation increased. The relative reduction in fuel consumption ranged from 6.1% to 7.9%, depending on the load level. The main results obtained in this test mode are shown in Table 3.

Table 3

Fuel flow measurement results at 2500 rpm

Torque M_{mot}, N·m	**Fuel flow, g·s^{-1}**		**Difference, g·s^{-1}**	**Difference, %**
	4-cylinders	**2-cylinders**		
5	0.441	0.403	0.038	8.68
10	0.512	0.472	0.040	7.86
15	0.583	0.541	0.042	7.25
20	0.654	0.610	0.044	6.77
25	0.725	0.679	0.046	6.38
30	0.796	0.748	0.048	6.06
40	0.939	0.886	0.052	5.57

Maximum fuel savings were observed at low loads (10 N·m). As the torque increased, the effect gradually decreased, but even at a load of 30 N·m, cylinder deactivation remained effective and provided a noticeable reduction in fuel consumption compared to four-cylinder operation.

At 3000 rpm, the positive effect of cylinder deactivation remained, but its magnitude was significantly lower compared to the 1600 and 2500 rpm modes. The relative reduction in fuel consumption ranged from 2.2% to 2.9%. The main results obtained in this test mode are shown in Table 4.

Table 4

Fuel flow measurement results at 3000 rpm

Torque M_{mot}, N·m	**Fuel flow, g·s^{-1}**		**Difference, g·s^{-1}**	**Difference, %**
	4-cylinders	**2-cylinders**		
5	0.539	0.529	0.010	1.84
10	0.622	0.608	0.013	2.16
15	0.704	0.687	0.017	2.40
20	0.787	0.766	0.020	2.59
25	0.869	0.845	0.024	2.75
30	0.952	0.924	0.027	2.88
40	1.117	1.082	0.034	3.08

Unlike the previous modes, maximum fuel savings were observed at higher loads, while at minimum torque values the deactivation effect was less pronounced. Nevertheless, at all points studied at this speed, cylinder deactivation did not lead to an increase in fuel consumption.

When the speed was further increased to 3500 rpm, the efficiency of cylinder deactivation decreased significantly. In the low load range, an increase in fuel consumption was recorded when the engine was running with two active cylinders compared to the base mode. The main results obtained in this test mode are shown in Table 5.

Table 5

Fuel flow measurement results at 3500 rpm

Torque M_{mot}, N·m	**Fuel flow, g·s^{-1}**		**Difference, g·s^{-1}**	**Difference, %**
	4-cylinders	**2-cylinders**		
5	0.656	0.667	-0.012	-1.77
10	0.753	0.761	-0.008	-1.08
15	0.851	0.855	-0.005	-0.54
20	0.948	0.949	-0.001	-0.12
25	1.046	1.043	0.002	0.23
30	1.143	1.137	0.006	0.52
40	1.338	1.325	0.013	0.96

A negative effect was observed at loads up to 20 N·m, with fuel consumption increasing by up to 1.1%. At higher loads, the difference between the modes decreased, but even at a load of 30 N·m, fuel savings did not exceed 1%.

The reduction in the effectiveness of cylinder deactivation at higher engine speeds can be attributed to increased gas exchange losses in the deactivated cylinders. Since the valve timing remains unchanged and the valves continue to operate, the deactivated cylinders act as passive gas pumps, increasing flow resistance and reducing the overall efficiency gain. In addition, at higher rotational speeds, the relative contribution of pumping losses to total engine losses decreases, which further limits the potential benefit of cylinder deactivation.

5 and 40 N·m are in another colour as extrapolated from real measurements by Trendline notice, in real experiments this data was not possible to measure by study limitation, but this data (points) is needed to calculate fuel combustion on constant speed, and hopefully it can be helpful for similar engines with electric cylinder deactivation projects.

Thus, the experimental results confirm that simplified electronic cylinder deactivation can provide measurable fuel efficiency benefits under specific operating conditions, while also highlighting the importance of considering engine speed and load limitations in practical applications.

Summary of experimental results

Calculating BSFC from the obtained values, it can be concluded that the engine remained more efficient in the low load zone when operating with two cylinders, i.e. it consumed less fuel while developing the same power. BSFC was calculated as:

$$BSFC = \frac{F_g}{P_e}, \tag{3}$$

where $BSFC$ – brake specific fuel consumption, g·kWh^{-1};
F_g – fuel mass flow, g·s^{-1};
P_e – engine power, kW.

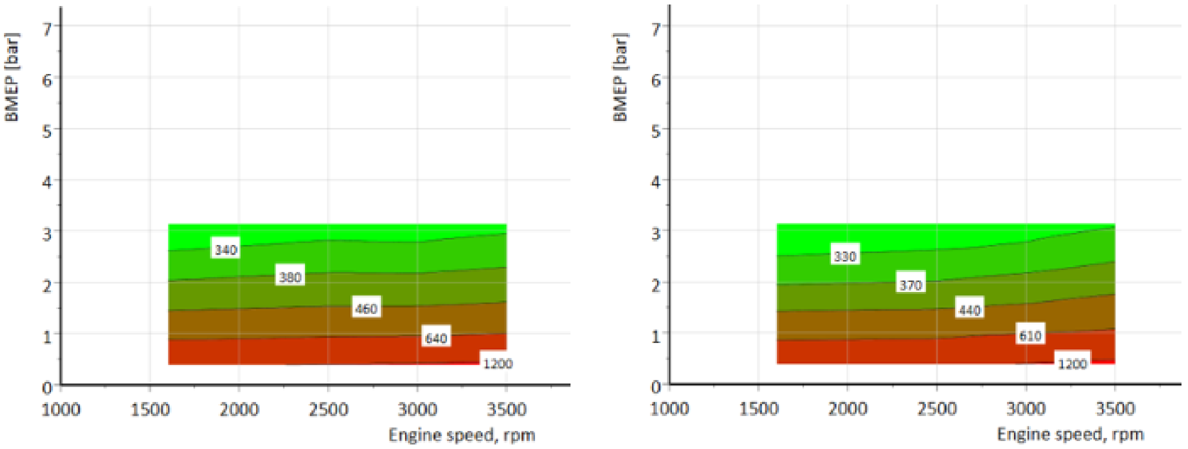

Fig. 3. **Comparison of BSFC for four- and two-cylinder operation**

Fuel consumption calculations are based on the 1998–2001 model year Toyota Corolla 8 (E110). This model is the latest to be produced at the Toyota factory with a 4A-FE engine. Modelling the 4A-FE engine in a Toyota Corolla 8 (E110) body, the best fuel economy is achieved at ~2200 rpm and 0.5 bar load.

Specifications of the car mass, wheel size and body geometry were obtained from open-source data [16].

As the gearbox ratios for the Toyota Corolla 8 (E110), as well as for comparable vehicles, were not available from open-access sources, they were determined using a gear ratio synthesis method based on the vehicle speed characteristics.

The results are presented in Table 6.

Table 6

Transmission characteristics

No.	Main Gear	Gear	Gear ratio, z	Maximum vehicle speed, v_{max}, km·h^{-1}
1.	4.06	1	3.50	45.2
2.		2	2.10	75.3
3.		3	1.50	105.5
4.		4	1.07	147.9
5.		5	0.82	193.0

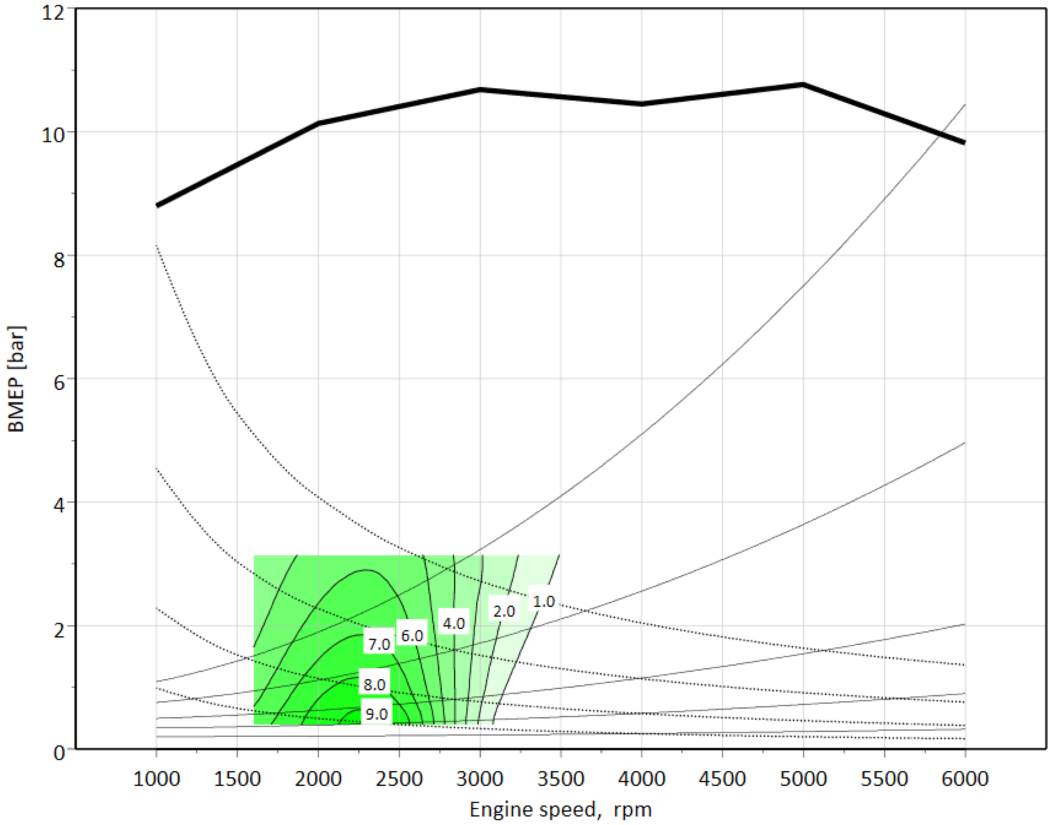

Fig. 4. **Engine map generated in Uniplot showing estimated fuel economy gain from cylinder deactivation, %**

At a constant speed, Toyota Corolla 8 (E110) could save fuel by electric cylinders cut off is given in Fig. 5.

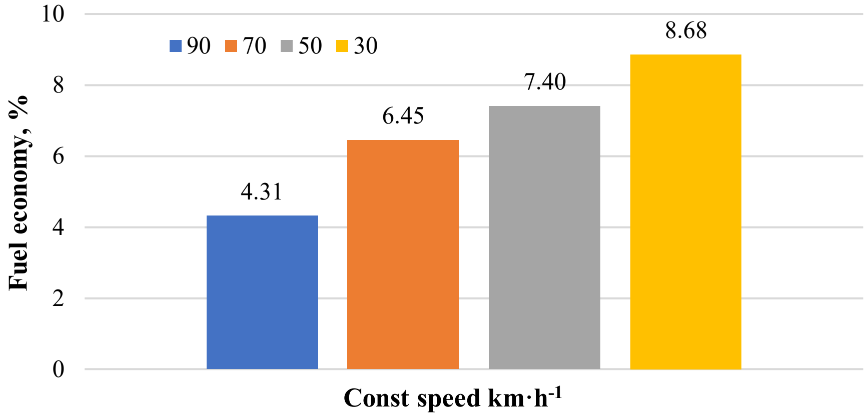

Fig. 5. **Toyota Corolla 8 (E110) fuel saving of cylinder cut off on constant speed**

Measurement uncertainty

The combined relative measurement uncertainty was evaluated using the root-sum-square (RSS) method, assuming independent input variables:

$$\delta = \sqrt{\delta_n^2 + \delta_{M_{mot}}^2 + \delta_{\rho_f}^2 + \delta_{m_f}^2 + \delta_t^2}\,, \tag{4}$$

where δ_n, δ_{Mmot}, $\delta_{\rho f}$, δ_{mf}, δ_t – represent the relative uncertainties of engine speed, torque, fuel density, fuel mass flow rate, and time measurement, respectively.

Based on the instrumental uncertainties summarized in Table 7, the overall relative measurement uncertainty was determined to be: $\delta = \pm 1.45\%$. The obtained relative measurement uncertainty (± 1.45%) is lower than the observed variation in the experimental data. Therefore, the influence of measurement error on the results is limited, and the obtained measurements can be considered reliable and representative for the analysis of engine fuel consumption characteristics.

Table 7

Instrumental uncertainties

Measuring instruments/sensor	Input parameter	Uncertainty, %
Speed	n, rpm	± 1
Torque, load cell sensor	M_{mot}, N·m	± 0.1
Fuel density	ρ_f, g·ml^{-1}	± 0.1
Fuel mass flow	m_f, g·s^{-1}	± 1
Time	t, sec	± 0.3

Limitations of the study

This study has a number of limitations that must be taken into account when interpreting the results and their possible practical application.

First, the experiments were conducted on an engine dynamometer, which ensures high repeatability of engine operating modes but does not allow for full reproduction of all dynamic conditions of vehicle operation on the road. In particular, the experiment did not take into account transient processes associated with sudden changes in load and rotational speed, which can affect the stability of engine operation when cylinders are deactivated.

Secondly, the scope of experimental measurements was limited to a crankshaft speed range of 1600 to 3500 rpm and torque ranges of 10 to 30 N·m. It was impossible to expand the study area due to design limitations of the engine test bench and increased vibrations at certain engine operating modes. As a result, the effect of cylinder deactivation at lower crankshaft speeds and higher loads was not considered.

Thirdly, cylinder deactivation in this work was implemented exclusively by shutting off the fuel injectors power supply, without shutting off the valve mechanism and without changing the gas distribution phases (valve timing). This solution deliberately simplifies the system but leads to additional gas exchange losses in the deactivated cylinders, which limits the potential effect of reducing fuel consumption and does not allow direct comparison of the results obtained with serial cylinder deactivation systems.

In addition, the study did not measure harmful emissions or the acoustic and vibration characteristics of the engine. These parameters can vary significantly when the engine is running with cylinders deactivated and require separate analysis.

These limitations do not reduce the reliability of the experimental data obtained within the scope of the tasks set, but they do define the boundaries of applicability of the results and directions for further research.

Conclusions

1. It has been experimentally confirmed that electronic cylinder deactivation in a SI engine without changing the gas distribution phases (valve timing) can reduce fuel consumption in low and medium load modes.

2. For the Toyota 4A-FE engine, the greatest effect of cylinder deactivation is observed in the crankshaft speed range up to 3000 rpm. The maximum recorded reduction in fuel consumption was up to 8.7% extrapolated area or 7.9% real measured area compared to the base mode of operation on four cylinders.
3. When the speed is increased to 3500 rpm, the efficiency of cylinder deactivation decreases sharply, and in a number of low-load modes, an increase in fuel consumption is observed, which indicates the upper limit of the applicability of this method.

Author contributions

Conceptualization, V.S.; methodology, V.S. and M.G.; investigation, V.S., writing – original draft preparation, V.S.; writing – review and editing, M.G.; visualization, V.S. All authors have read and agreed to the published version of the manuscript.

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