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Chapter

Work Cycle of Internal Combustion Engine Due to Rightsizing

Zbigniew J. Sroka

Abstract

It is worth still working on the development of the internal combustion engine, because its time was not yet over. This was demonstrated by the author's review of the literature, indicating at least the perspective of 2050 the universality of the engine as the primary propulsion or support in hybrid transport units. The presented considerations may have a broader perspective, when the thermodynamic problems of a thermal machine such as an internal combustion engine are indicated. This chapter deals with the issues of changing the swept volume known as downsizing/rightsizing. An equivalent swept volume was introduced, defined by the coefficients determining changes in the cylinder diameter and the stroke of the piston. An attempt was made to find the mutual relations to the efficiency of the work cycle and engine operating parameters. The research methodology was proposed as a mix of laboratory tests and theoretical analyses, on the basis of which it was established that while maintaining the same value of the downsizing index, despite the various permissible combinations of cylinder diameter and piston stroke changes, the cycle efficiency remains unchanged. The engine operating parameters are changing, resulting from the use of support systems for rightsizing geometric changes.

Keywords: internal combustion engine, work cycle, rightsizing

1. Introduction - the essence of the research problem

It is the beginning of 2021 and internal combustion engines are not yet dead, although many people predicted their significant reduction in connection with the introduction of hybrid drive in vehicles [1]. And yet this drive still has an internal combustion engine!

When in 2007 the 2nd PTNSS Engine Congress was held in Krakow, in Poland, an international group of scientists and researchers identified three scenarios for the development of internal combustion engines:

I. short-term (until 2017): improving the design of internal combustion engines to meet ecological standards and the use of alternative fuels,

II. mid-term (2017–2037): development of hybrid systems,

III. long-term (over 30 years, i.e. over 2037): independence of transport from fossil fuels [2].

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With the passage of years and the verification of predictions on the basis of real data, the need for the development of internal combustion engines was indicated indirectly in connection with the change from linear to exponential transport index passenger-kilometer, which forces the increase in the production of motor vehicles (passenger cars, trucks and busses) from the current 70 million annually to over 107 million units in 2050 [3, 4].

On August 17, 2017, Norman Mayersohn, in The New York Times magazine, in an article entitled "The Internal Combustion Engine Is Not Dead Yet", interviewed Professor John Heywood, the undisputed guru in the design and testing of internal combustion engines. Professor Heywood pointed to the presence of internal combustion engines with a significant share in 2050 – quotation: *„Definitely. John Heywood, a professor of mechanical engineering at the Massachusetts Institute of Technology, predicts that in 2050, 60 percent of light-duty vehicles will still have combustion engines, often working with electric motors in hybrid systems and largely equipped with a turbocharger. Vehicles powered purely by batteries, he estimates, will make up 15 percent of sales"* [5].

In April 2020, the virtual 41st International Vienna Motor Symposium took place (due to the COVID19 coronavirus pandemic), during which the development of internal combustion engines was discussed [6].

It was the time of the "New and Optimized Engines" session, during which Ford presented the latest solutions in the field of EcoBoost technology, emphasizing the importance of charging [7].

Toyota discussed the 1.5 Liter engine solutions from the Toyota New Global Architecture (TNGA) platform, emphasizing the importance of balance between design and application. Among other things, it was discussed: hydraulically variable valve timing, very high compression moderated by Atkinson cycle, longer bore and stroke ratio, application of multi-hole injector system to achieve "high-speed combustion", resulting more than 40% in thermal efficiency [8].

The authors of another presentation mentioned a similar meaning of the modular construction and technological platform for internal combustion engines [9].

The modularity of engines, but in relation to Diesel, was discussed during the session "New SI and CI Engines" [10], where the modular solutions of the BMW company were demonstrated.

Similar to Toyota TNGA solutions at Mercedes-Benz is FAME (Family of Modular Engines), which involves the creation of subsequent engine versions based on the M-254 engine. [11]. Everything is dedicated to the fulfillment of global CO_2 fleet targets. Quotation *„..the M 254 paves the way with regard to CO2- neutrality and air quality approaching the sustainability strategy Ambition 2039.*

The importance of the filling process both on the supercharging side and the change of the geometry of the suction system were emphasized. Attention was also paid to the reduction of friction in the piston-cylinder liner system. The summary of the whole was as follows - a quote *... the internal combustion engine is still far from being at the end of the road!*

Environmental protection is the dominant topic in all publications. This is also the case in another study [12], where VW indicated numerous possibilities of meeting Euro 6d standards.

Subsequent studies indicate the importance of alternative fuels, with particular emphasis on hydrogen [13, 14]. The full usefulness of typical hydrogen-powered combustion engines has been demonstrated in relation to the still developed Fuel-Cell technology.

The extensive discussion is not forgotten engine applications truck [15]. Here importance is the durability of use. Considerations were conducted in the perspective of 2050!

Finally, in the general discussion, the development scenarios of combustion engines were indicated [16, 17]. In the short-term perspective, i.e. until 2030, the importance of environmental protection was emphasized, and in the longer term, i.e. until 2050, attention was additionally paid to the importance of sustainability and safe use of engines in the environment.

The above considerations have a common denominator - the world does not give up on internal combustion engines. Research centres and universities are still working on developing the design of this heat machine.

One of the development trends is the downsizing of combustion engines that has been going on for over ten years and has recently been modified towards rightsizing. This trend is not so much about reducing the displacement as it is about choosing the right size in order to achieve a balance between customer expectations for operating comfort and the manufacturer's ability to reduce fuel consumption and CO_2 emissions.

The essence of the research problem presented in this chapter is to demonstrate the existence of parameters describing the engine displacement volume, which is the dominant feature of downsizing/rightsizing, enabling the assessment of the effectiveness of changes in the IC engine operation indicators.

This means that the main research question can be formulated as follows - is it possible to replace the displacement volume of an internal combustion engine in the considerations on its work cycle, a certain equivalent volume, and can the application of the new solution be used to investigate the cause-and-effect relationships between thermodynamic parameters and internal combustion engine performance indicators?

The search for an answer to the research question is associated with the analysis of the thermodynamic work cycle of the downsized engine. The impact of changes in the swept volume and the equivalent volume on the parameters of the comparative work cycle for similar values of the downsizing index was assessed.

2. Rightsizing the internal combustion engine

Development works related to the rightsizing concept are focused primarily on increasing the specific volumetric power. These are therefore actions similar to those previously undertaken for downsizing, when reducing the displacement while maintaining or increasing the engine power per liter of displacement.

The essence of downsizing results from the power equation, which takes the form (1) [18, 19].

$$N_e = p_e V_{ss} \frac{n}{30\tau} \tag{1}$$

By changing the engine's displacement according to the rule - the volume "after" is smaller than "before", i.e. $V_{ssd} < V_{ss}$, (where: V_{ssd} is the engine swept volume after downsizing) and at the same time keeping the engine power $N_{ed} = N_e$ (where: N_{ed} - downsizing engine power), Eq. (2) is obtained

$$p_e V_{ss} \frac{n}{30\tau} = p_{ed} V_{ssd} \frac{n_d}{30\tau_d} \tag{2}$$

Indicators with the index "d" indicate downsizing data.

Assuming constancy engine speed $n_d = n$ and constancy of the number of strokes $\tau_d = \tau$, to give (3)

$$p_{ed} = p_e\left(\frac{V_{ss}}{V_{ssd}}\right) \tag{3}$$

In turn, fuel consumption expressed as the specific value (g_e) can be written as (4)

$$g_e = \frac{1}{\eta_e W_u} \tag{4}$$

where the useful efficiency η_e is expressed by the relation (5)

$$\eta_e = \frac{MRL_p p_e T_o}{\eta_v W_u p_o} \tag{5}$$

With a reasonable assumption of unchanged value beyond the engine operating after downsizing, useful efficiency becomes dependent only on the brake mean effective pressure (p_e = *BMEP*).

Brake specific fuel consumption (*BSFC* = g_e) can also be expressed by defining the actual amount of fuel burned per unit time, giving the unit of power (6).

$$g_e = \frac{G_e}{N_e} \tag{6}$$

Keeping the constant useful power after downsizing, i.e. $N_{ed} = N_e$, the following Eq. (7) is obtained

$$\frac{G_{ed}}{g_{ed}} = \frac{G_e}{g_e} \tag{7}$$

which, taking into account the close relationship between fuel consumption and the concentration of carbon dioxide in exhaust gases, will change into (8)

$$CO_{2d} = CO_2\left(\frac{g_{ed}}{g_e}\right) \tag{8}$$

The changes caused by the downsizing idea can be illustrated in the diagrams - **Figure 1**.

If, in the downsizing of the internal combustion engine, the reduction of the engine speed (*downspeeding*) is made, the effect of reducing fuel consumption and limiting carbon dioxide emissions will be enhanced. For this case, assuming the stability of the parameter values as in Eq. (9)

$$V_{ssd2} = V_{ssd1}, N_{ed2} = N_{ed1}, \tau_{d2} = \tau_{d1}, \tag{9}$$

and changing only the speed $n_{d2} < n_{d1}$, one gets (10) and (11)

$$p_{ed1} V_{ssd1} \frac{n_{d1}}{30\tau_{d1}} = p_{ed2} V_{ssd2} \frac{n_{d2}}{30\tau_{d2}} \tag{10}$$

$$p_{ed2} = p_{ed1}\left(\frac{n_{d1}}{n_{d2}}\right) \tag{11}$$

Index 1 represents the downsized base engine.

Index 2 denotes the downsized engine with changed (reduced) rotational speed.

The measure of engine modernization, both for downsizing and rightsizing, is the degree (index) of changes, which is defined in various ways [19–21]. Regardless

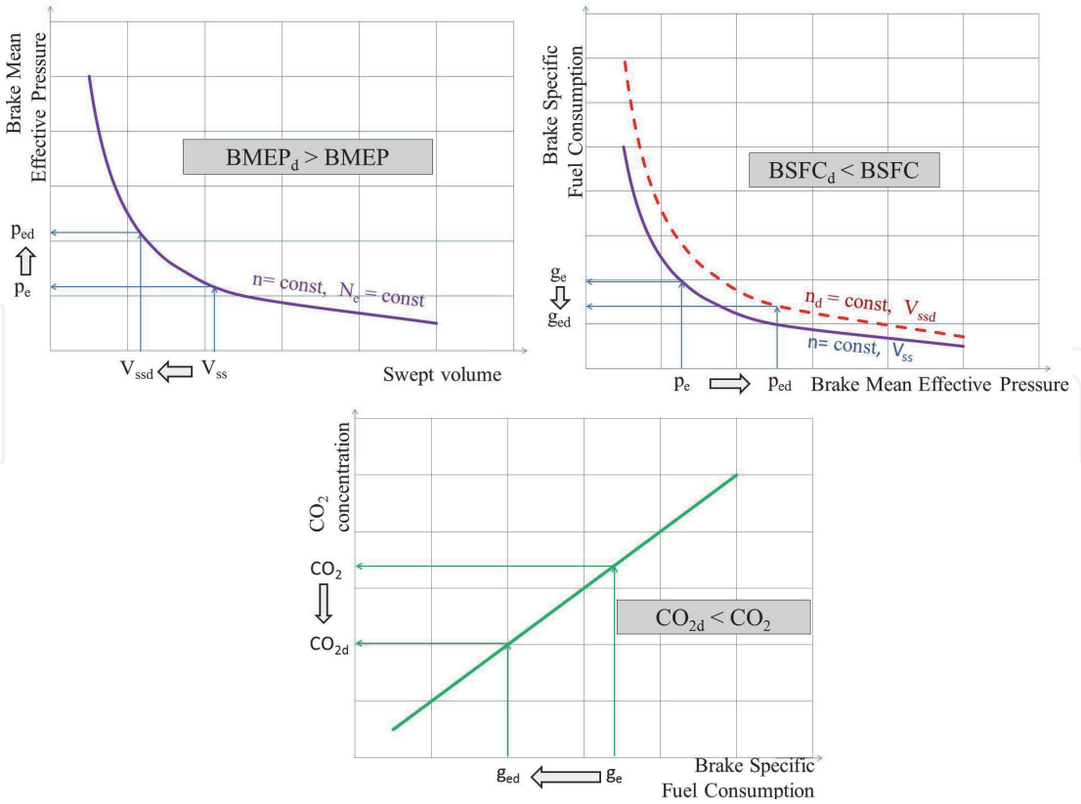


Figure 1.
The idea of downsizing.

of the definition, this indicator shows the change or degree of residue after the reduction or increase of the swept volume.

Unlike all the others, the author defined the downsizing index (W_d) based on the degrees of changes in the components describing the cylindrical combustion chamber (equivalent volume), which dominates the design of internal combustion engines [19]. According to this definition, the downsizing index can be described as in formula (12).

$$W_d = 1 - AB^2 \quad \text{dla} \quad A = \frac{S_d}{S} \qquad B = \frac{D_d}{D} \tag{12}$$

In the graphic interpretation, theoretically and practically three forms of changes in the swept volume can be distinguished - as in **Figure 2**.

By implementing the idea of rightsizing, it is possible to obtain the same changes in the W_d index at different values of the piston stroke and the cylinder diameter, which results from the different values of the coefficients A and B (see formula 12). The downsizing/rightsizing combinations are presented in the form of a matrix of changes in the coefficients A and B - **Figure 3**. The matrix can show two volatility zones of the W_d indicator: downsizing and upsizing, important in considering rightsizing.

Having knowledge of the design of the combustion chamber and the crank system in the commonly accepted geometric relationships between the cylinder diameter and the stroke [18, 22], as well as based on the actual relationships of these parameters determined on the basis of the engines from the Engine of the Year competition over the years 1999–2019 [19, 20] it was possible to determine the real ranges of variability of the ratio of the cylinder diameter to the piston stroke, which is from 0.77 to 1.30, which results in the value of the W_d index in the range of minus −1.20 on the upsizing side and plus +0.51 in the case of downsizing.

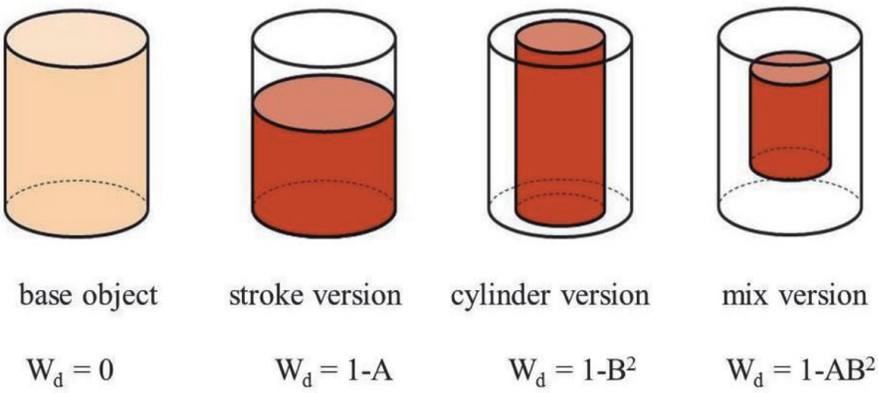


Figure 2.
Forms of downsizing [19].

										A									
	-1,97	-1,77	-1,58	-1,39	-1,21	-1,04	-0,87	-0,71	-0,56	**1,41**	-0,41	-0,28	-0,15	-0,02	0,10	0,20	0,31	0,40	0,49
	-1,84	-1,65	-1,47	-1,28	-1,11	-0,94	-0,79	-0,63	-0,49	**1,35**	-0,35	-0,22	-0,09	0,02	0,14	0,24	0,34	0,43	0,51
	-1,73	-1,54	-1,37	-1,20	-1,03	-0,87	-0,72	-0,57	-0,43	**1,30**	-0,30	-0,17	-0,05	0,06	0,17	0,27	0,36	0,45	0,53
	-1,63	-1,45	-1,28	-1,12	-0,96	-0,80	-0,66	-0,51	-0,38	**1,25**	-0,25	-0,13	-0,01	0,10	0,20	0,30	0,39	0,47	0,55
	-1,52	-1,35	-1,19	-1,03	-0,88	-0,73	-0,59	-0,45	-0,32	**1,20**	-0,20	-0,08	0,03	0,13	0,23	0,33	0,41	0,49	0,57
	-1,42	-1,25	-1,10	-0,94	-0,80	-0,66	-0,52	-0,39	-0,27	**1,15**	-0,15	-0,04	0,07	0,17	0,26	0,35	0,44	0,51	0,59
	-1,33	-1,18	-1,02	-0,88	-0,73	-0,60	-0,47	-0,34	-0,22	**1,11**	-0,11	0,00	0,10	0,20	0,29	0,38	0,46	0,53	0,60
	-1,21	-1,06	-0,91	-0,77	-0,64	-0,51	-0,39	-0,27	-0,16	**1,05**	-0,05	0,05	0,15	0,24	0,33	0,41	0,49	0,56	0,62
	-1,08	-0,94	-0,80	-0,67	-0,55	-0,43	-0,31	-0,20	-0,09	**0,99**	0,01	0,11	0,20	0,28	0,37	0,44	0,51	0,58	0,64
B	**1,45**	**1,40**	**1,35**	**1,30**	**1,25**	**1,20**	**1,15**	**1,10**	**1,05**	**W_d**	**1,00**	**0,95**	**0,90**	**0,85**	**0,80**	**0,75**	**0,70**	**0,65**	**0,60**
	-1,08	-0,94	-0,80	-0,67	-0,55	-0,43	-0,31	-0,20	-0,09	**0,99**	0,01	0,11	0,20	0,28	0,37	0,44	0,51	0,58	0,64
	-1,00	-0,86	-0,73	-0,61	-0,48	-0,37	-0,26	-0,15	-0,05	**0,95**	0,05	0,14	0,23	0,31	0,39	0,47	0,53	0,60	0,66
	-0,87	-0,74	-0,62	-0,50	-0,39	-0,28	-0,18	-0,08	0,02	**0,89**	0,11	0,20	0,28	0,36	0,43	0,50	0,56	0,63	0,68
	-0,79	-0,67	-0,55	-0,44	-0,33	-0,22	-0,12	-0,03	0,06	**0,85**	0,15	0,23	0,31	0,39	0,46	0,52	0,58	0,65	0,69
	-0,68	-0,57	-0,46	-0,35	-0,25	-0,15	-0,06	0,03	0,12	**0,80**	0,20	0,28	0,35	0,42	0,49	0,55	0,61	0,66	0,71
	-0,52	-0,42	-0,32	-0,23	-0,13	-0,04	0,04	0,12	0,20	**0,73**	0,28	0,35	0,41	0,48	0,54	0,59	0,65	0,69	0,74
	-0,47	-0,37	-0,28	-0,18	-0,09	-0,01	0,07	0,15	0,23	**0,70**	0,30	0,37	0,43	0,49	0,55	0,61	0,66	0,70	0,75
	-0,39	-0,29	-0,20	-0,11	-0,03	0,05	0,13	0,20	0,27	**0,66**	0,34	0,41	0,47	0,52	0,58	0,63	0,68	0,72	0,76
	-0,27	-0,19	-0,10	-0,02	0,05	0,13	0,20	0,27	0,33	**0,61**	0,40	0,45	0,51	0,56	0,61	0,66	0,70	0,74	0,78

no real application

upsizing

downsizing

no real application

Figure 3.
Matrix of changes to the downsizing/rightsizing index according to various combinations of coefficients A and B (according to formula 12).

In order to maintain the operational parameters of the internal combustion engine, while reducing its stroke volume, it is necessary to implement new or intensify the existing functions performed by individual structural and functional systems in the engine. Among them, an important place is occupied by: direct fuel injection, charging, variable valve timing, variable compression ratio. And the whole thing is controlled by electronics [23–25].

The idea of direct fuel injection developed differently in the two different engine types (diesel and gasoline). It has been used almost always in diesel engines, but the implementation of the Common Rail system by the Denso/Toyota corporation played a special role. It happened in 1995, although the idea was known as early as 1916 (Vickers company) [26]. However, at that time, there was no technology of obtaining high pressure, atomization of fuel drops and the possibility of multiple fuel injection in one cycle [27]. Today, as a result of this, fuel consumption is

reduced and the emission of harmful exhaust components is significantly reduced due to the lower temperature in the combustion chamber. Additionally, a lower noise level is achieved, which significantly improves the comfort of operation [28].

On the other hand, the implementation of direct gasoline injection in spark ignition engines resulted in greater positive effects in the economic and ecological balance of engine development. The first attempts to inject gasoline directly into the combustion chamber were carried out by Jonas Hesselman in 1925, but only the solution proposed by Mitsubishi in 1996 brought success in development. This solution is known as GDI - Gasoline Direct Injection [29]. Gasoline injection, carried out in at least two phases during the intake and compression stroke, allows for stratified combustion, including combustion of very poor mixtures (50: 1 versus stoichiometric - conventional 14.7: 1), which in turn helps to increase the compression ratio without knocking effect. The use of a special combustion chamber geometry in the piston crown and thus achieving a load swirl increases engine power with a simultaneous reduction in fuel consumption. The disadvantage of this system is, unfortunately, the increase in nitrogen oxides emissions, which means that the engine must be equipped with a reducing catalyst and exhaust gas recirculation system. Of great importance in the implementation of GDI is control, including adaptive systems [30]. The use of direct injection fits very well into the architecture of the engine covered by downsizing/rightsizing because it directly complements the power loss resulting from changes in geometry.

Another downsizing/rightsizing support system is the charging, the presence of which is essential for proper cylinder filling. As early as 1885, Gottlieb Daimler noticed the need for charging to increase the filling level in his patent about the need to increase the air pressure above atmospheric at the beginning of each cycle [18]. Then came the concept of recycling the energy wasted with the exhaust gas outlet and in 1916 Auguste Reteau built the first turbocharger. For many years, the concept of a single turbocharger functioned until the appearance of the Honeywell turbocharger, where, due to the limited response time to changes in engine load on a common axle, two compressor wheels appeared next to one turbine. The engine with such a system works more efficiently, especially in the lower engine speed (rpm) and load ranges. In the following years, various solutions began to appear, including variable VNT (Variable Nozzle Turbine) settings. An interesting solution is the system of two turbochargers working in parallel, which replace one large one. Thanks to this solution, the turbochargers are smaller (in line with the downsizing idea), which results in less heat loss to the atmosphere.

There are also combinations of mechanical, electric and traditional charging. [31–33]. Supercharging is the simplest form of supporting the downsizing/rightsizing engine, both in terms of power loss and by creating conditions for burning poor mixtures to meet ecological requirements.

The improvement of volumetric efficiency is also achieved by the application of variable valve timing systems. The variable valve timing system ensures that the angles and times of opening and closing the valves are matched to the current load and engine speed.

There are many variable valve timing systems which undergo successive design transformations and take different names depending on the manufacturer [34]. The first variable valve timing system appeared in 1981 on Alfa Romeo engines, but it was only the introduction of electronic control in 1989 by Honda that allowed the development of this design known as VTEC (Variable Valve Timing and lift Electronic Control), and in the latest version i- VTEC (i - intelligent system that works ahead).

In contrast, the VarioCam system, designed by Porsche in 1992, altered the position of the valves by changing the tension in the chain connecting the intake

and exhaust camshafts. Today the system is developed and also offers valve lift capability. Another example is the Valvetronic system from BMW with full control of the intake valve lift, which significantly reduces flow losses and the reaction time to load changes is reduced to a minimum.

Yet another example in this field is Ford's TI-VCT (Twin Independent - Variable Camshaft Timing) system of independent inlet and outlet valve operation, whose main advantage over other systems is better cylinder filling and scavenging the combustion chamber.

The variable valve timing system is a good complement to the downsizing/rightsizing technique by being able to reduce flow losses due to smaller valve dimensions and by ensuring that the combustion chamber is properly filled to maintain or increase engine efficiency.

When supercharging spark-ignition engines, there may be a risk of spontaneous combustion, which is inherently undesirable. In order to prevent this, the compression ratio should be lowered, which in turn determines the pressure in the combustion chamber, and this affects the engine power throughout its entire operating range. The solution to this problem is a system with a variable compression ratio.

The principle of operation of the variable compression ratio system - VCR is associated with a change in the volume of the compression chamber with the change of load. There are several technical solutions to this issue. One of them is the change of stroke in the crank mechanism (Multi Cycle Engine 5, implemented by Peugeot).

Another way is the angular displacement of the cylinder head offered by SAAB (SVC system - Saab Variable Compression). Yet another solution is the dynamic movement of the entire crank system (Cortina VC - Variable Compression). The GoEngine solution is structurally interesting as it provides a change in the compression ratio in the range from 8: 1 to 18: 1. A significant advantage of this system is the possibility of a significant (up to 20%) extension of the expansion stroke in relation to the compression stroke, which provides better conditions for burning the fuel dose, generates more favorable pressure distribution on the piston crown and lowers the exhaust gas temperature. A variable compression ratio system, by varying the cylinder volume, can be considered one of the forms of dynamic downsizing/rightsizing, not as a support system.

From engineering practice, there are a number of examples of the development of the downsizing/rightsizing idea. We can even mention the engines installed in Ford or Volkswagen vehicles.

The Ford's engine with a displacement of 2.3 dm^3 V6 was reduced to 2.0 dm^3 and 1.6 dm^3, to finally reach the spectacular 0.999 dm^3 EcoBoost - **Figure 4**. Some people consider the engine with a displacement of 5.0 dm^3 Coyote to be the progenitor of all downsizing/rightsizing changes. This makes changes a kind of cascade of actions.

In turn, the Volkswagen engines changed the displacement from 2.8 dm^3 or 2.0 dm^3 to 1.8 dm^3, and then to 1.4 dm^3, fulfilling the downsizing assumption, and with sustainable development (rightsizing) the 1.4 dm^3 engine was replaced with 1.5 dm^3.

On a large scale, the trend of changing the displacement volume is well represented by the engines considered in the international competition Engine of The Year, which since 1999 has been organized by the magazine Engine Technology International - UK & International Press [35]. The winning engines in all categories show a clear trend of change in displacement over the years. It is expressed by an increase in the specific power and a decrease in carbon dioxide emissions, which increase with a decrease in the stroke volume - **Figure 5**.

In automotive practice, internal combustion engines designed in the downsizing and rightsizing technique can be found in cars with a whole package of

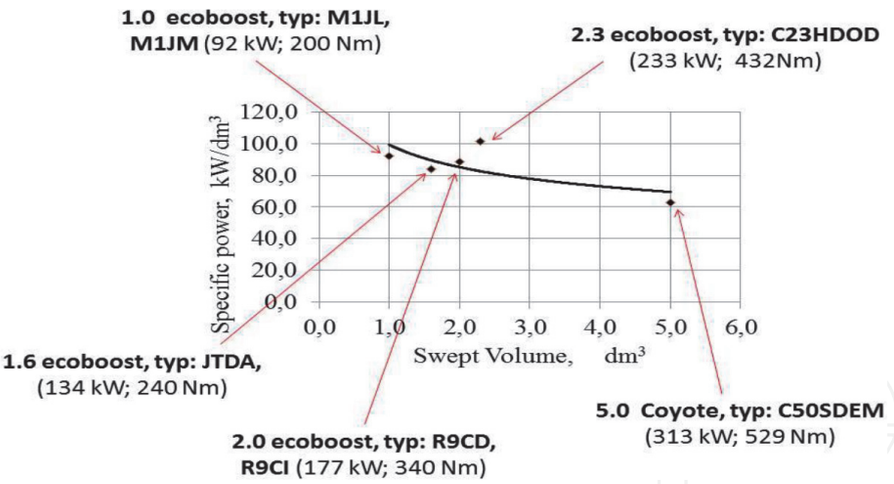


Figure 4.
Rightsizing on the example of Ford's engines.

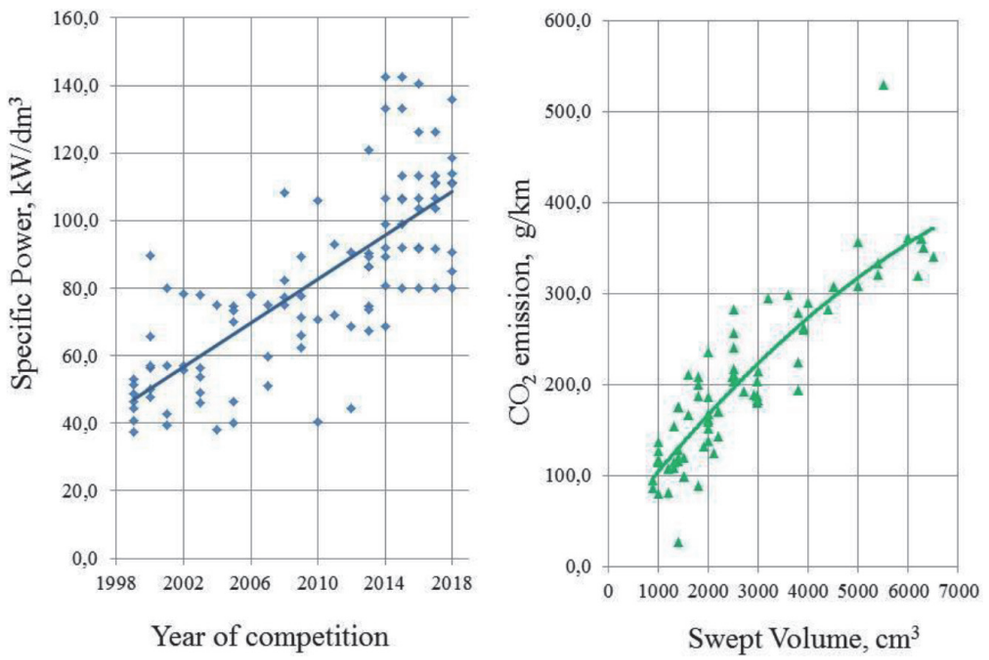


Figure 5.
The specific power of combustion engines together with the carbon dioxide emissions of the "winners" in the engine of the year competition in all categories.

pro-ecological solutions and are included in marketing names, for example: EcoBoost/Econetic (Ford) or Blue Motion (Volkswagen) [2].

3. Efficiency of the generalized engine work cycle in terms of rightsizing - research methodology

In the combustion chamber of a reciprocating internal combustion engine, the fuel mixed with air creates a working medium that undergoes thermodynamic changes, related, among other things, to the volume of the combustion space. These changes are repeatable, although their magnitude depends on the current operating conditions of the engine. The occurring transformations create the engine work cycle, mathematically described in various ways [36–38]. In a generalized form, corresponding to all known theories of internal combustion engines, the work cycle

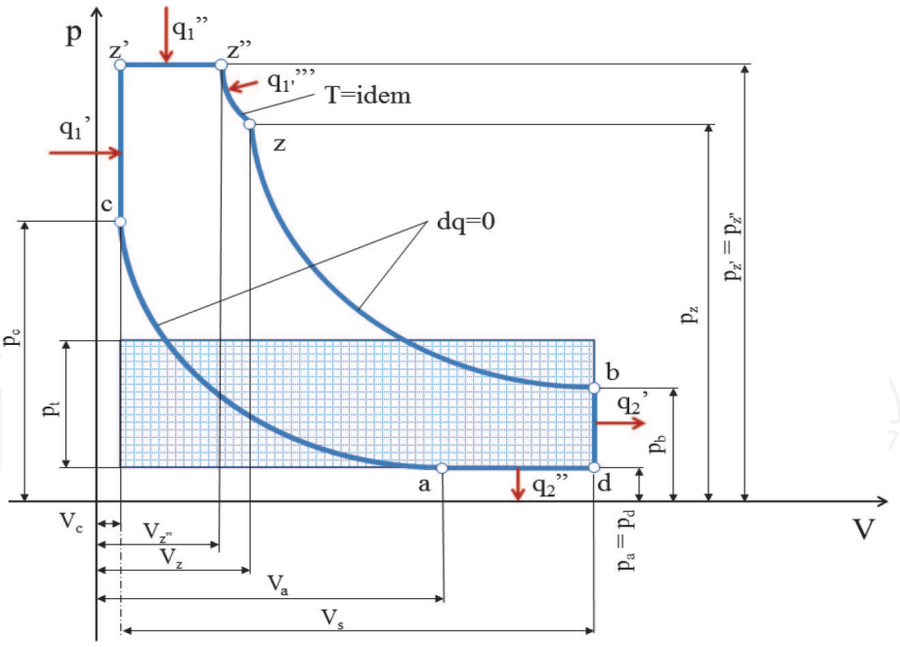


Figure 6.
Generalized thermodynamic work cycle of a four-stroke internal combustion engine [36].

can be described by the efficiency (ηt) as per formula (13) and expressed graphically as in **Figure 6**.

$$\eta_t = 1 - \frac{\frac{\lambda_p \rho_p \varepsilon_s^{\kappa-1}}{\delta^{\kappa-1}} + \kappa(\rho' - 1) - \rho'}{\varepsilon_s^{\kappa-1}\left\{\lambda_p\left[\kappa\rho_p - (\kappa-1)\left(1 + \rho_p \ln \rho_T\right)\right] - 1\right\}} \tag{13}$$

The individual dimensionless quantities appearing in formula (13) are described in accordance with **Figure 6** [19].

- degree of pressure increase during isochoric heat transfer

$$\lambda_p = \frac{p_{z'}}{p_c} = \frac{p_{z''}}{p_c} \tag{14}$$

- degree of expansion during isobaric heat transfer

$$\rho_p = \frac{V_{z''}}{V_{z'}} = \frac{V_{z''}}{V_c} \tag{15}$$

- effective compression ratio

$$\varepsilon_s = \frac{V_a}{V_c} \tag{16}$$

- isentropic exponent

$$\kappa = \frac{c_p}{c_v} \tag{17}$$

- degree of another expansion process

$$\delta = \frac{V_b}{V_z} \tag{18}$$

- degree of pre-compression when heat is drained at constant pressure

$$\rho' = \frac{V_d}{V_a} = \frac{V_b}{V_a} \tag{19}$$

- degree of expansion during isothermal heat transfer

$$\rho_T = \frac{V_z}{V_{z''}} \tag{20}$$

- geometric compression ratio

$$\varepsilon = \frac{V_b}{V_c} = \frac{V_d}{V_c} \tag{21}$$

By introducing the quantities expressed by the formulas (14)–(21) into the formula (13), one can obtain relationships that emphasize the changes in various volumes, which can be used to describe the changes caused by downsizing (22)

$$\eta_t = 1 - \frac{\frac{\lambda_p \left(\frac{V_{z''}}{V_c}\right)\left(\frac{V_a}{V_c}\right)^{\kappa-1}}{\left(\frac{V_b}{V_z}\right)^{\kappa-1}} + \kappa\left[\left(\frac{V_b}{V_a}\right) - 1\right] - \frac{V_b}{V_a}}{\left(\frac{V_a}{V_c}\right)^{\kappa-1}\left\{\lambda_p\left[\kappa\left(\frac{V_{z''}}{V_c}\right) - (\kappa-1)\left(1 + \left(\frac{V_{z''}}{V_c}\right)\ln\left(\frac{V_z}{V_{z''}}\right)\right)\right] - 1\right\}} \tag{22}$$

λp, Va, Vz, Vz", κ are components resulting from the properties of the fuel used and the logistics of the combustion process, while V_b and V_c are design parameters of the internal combustion engine related to the combustion space, and therefore related to the rightsizing operation.

The introduction to formula (22) of the variables A and B from formula (12) gives a full picture of changes in thermodynamic transformations in the theoretical cycle of the downsizing/rightsizing engine. When assessing the effectiveness of applying the rightsizing idea, three cases can be considered:

1. all the considered components are subject to change, that is: the displacement volume Vsd ≠ Vs together with the compression volume $V_{cd} \neq V_c$ and the compression ratio $\varepsilon_d \neq \varepsilon$ (23)

$$\eta_{td} = 1 - \frac{\frac{\lambda_{pd}\left(\frac{V_{z''d}}{V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}AB^2}\right)\left(\frac{V_{ad}}{V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}AB^2}\right)^{\kappa_d-1}}{\left(\frac{\left(V_s+V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}\right)AB^2}{V_{zd}}\right)^{\kappa_d-1}} + \kappa_d\left[\left(\frac{\left(V_s+V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}\right)AB^2}{V_{ad}}\right) - 1\right] - \frac{\left(V_s+V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}\right)AB^2}{V_{ad}}}{\left(\frac{V_{ad}}{V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}AB^2}\right)^{\kappa_d-1}\left\{\lambda_{pd}\left[\kappa_d\left(\frac{V_{z''d}}{V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}AB^2}\right) - (\kappa_d-1)\left(1 + \left(\frac{V_{z''d}}{V_c\frac{(\varepsilon-1)}{(\varepsilon_d-1)}AB^2}\right)\ln\left(\frac{V_{zd}}{V_{z''d}}\right)\right)\right] - 1\right\}} \tag{23}$$

If we assume that the selection of the compression ratio for the downsizing/rightsizing engine will be made on the basis of experimental data, e.g. by comparing the compression ratio values of the engines included in the *Engine of the Year* competition, then for typical examples the relationship between ε and ε_d was identified [19] (16).

$$\varepsilon_d = 0.547\varepsilon + 4.239 \tag{24}$$

It means the possibility of introducing a new coefficient (C), expressed by the relation (25).

$$\frac{\varepsilon_d - 1}{\varepsilon - 1} = C \tag{25}$$

After taking into account the dependence (25), the formula describing the theoretical efficiency of the engine work cycle takes the form (26).

$$\eta_{td} = 1 - \frac{\frac{\lambda_{pd}\left(\frac{V_{z''d}}{V_c\frac{AB^2}{C}}\right)\left(\frac{V_{ad}}{V_c\frac{AB^2}{C}}\right)^{\kappa_d-1}}{\left(\frac{\left(V_s+V_c\frac{1}{C}\right)AB^2}{V_{zd}}\right)^{\kappa_d-1}} + \kappa_d\left[\left(\frac{\left(V_s+V_c\frac{1}{C}\right)AB^2}{V_{ad}}\right)-1\right] - \frac{\left(V_s+V_c\frac{1}{C}\right)AB^2}{V_{ad}}}{\left(\frac{V_{ad}}{V_c\frac{AB^2}{C}}\right)^{\kappa_d-1}\left\{\lambda_{pd}\left[\kappa_d\left(\frac{V_{z''d}}{V_c\frac{AB^2}{C}}\right)-(\kappa_d-1)\left(1+\left(\frac{V_{z''d}}{V_c\frac{AB^2}{C}}\right)\ln\left(\frac{V_{zd}}{V_{z''d}}\right)\right)\right]-1\right\}} \tag{26}$$

2. the following are subject to change: the swept volume $V_{sd} \neq V_s$ and the compression volume $V_{cd} \neq V_c$ without changing the compression ratio $\varepsilon_d = \varepsilon$ (27)

$$\eta_{td} = 1 - \frac{\frac{\lambda_{pd}\left(\frac{V_{z''d}}{V_cAB^2}\right)\left(\frac{V_{ad}}{V_cAB^2}\right)^{\kappa_d-1}}{\left(\frac{(V_s+V_c)AB^2}{V_{zd}}\right)^{\kappa_d-1}} + \kappa_d\left[\left(\frac{(V_s+V_c)AB^2}{V_{ad}}\right)-1\right] - \frac{(V_s+V_c)AB^2}{V_{ad}}}{\left(\frac{V_{ad}}{V_cAB^2}\right)^{\kappa_d-1}\left\{\lambda_{pd}\left[\kappa_d\left(\frac{V_{z''d}}{V_cAB^2}\right)-(\kappa_d-1)\left(1+\left(\frac{V_{z''d}}{V_cAB^2}\right)\ln\left(\frac{V_{zd}}{V_{z''d}}\right)\right)\right]-1\right\}} \tag{27}$$

3. the third case is the change of the swept volume $V_{sd} \neq V_s$ and the compression ratio $\varepsilon_d \neq \varepsilon$ without changing the compression space $V_{cd} = V_c$ (28)

$$\eta_{td} = 1 - \frac{\frac{\lambda_{pd}\left(\frac{V_{z''d}}{V_c}\right)\left(\frac{V_{ad}}{V_c}\right)^{\kappa_d-1}}{\left(\frac{V_sAB^2+V_c}{V_{zd}}\right)^{\kappa_d-1}} + \kappa_d\left[\left(\frac{V_sAB^2+V_c}{V_{ad}}\right)-1\right] - \frac{V_sAB^2+V_c}{V_{ad}}}{\left(\frac{V_{ad}}{V_c}\right)^{\kappa_d-1}\left\{\lambda_{pd}\left[\kappa_d\left(\frac{V_{z''d}}{V_c}\right)-(\kappa_d-1)\left(1+\left(\frac{V_{z''d}}{V_c}\right)\ln\left(\frac{V_{zd}}{V_{z''d}}\right)\right)\right]-1\right\}} \tag{28}$$

In the test evaluation methodology, the real values of A and B coefficient pairs are introduced from the matrix described in **Figure 2**. This way, changes in the thermodynamic work cycle efficiency can be calculated. The rest of the data was taken from research on the 1.4 TSI, 1.5 TFSI, 1.8 T and 2.0 TDI engines, which are an example of a link in the downsizing/rightsizing chain of Volkswagen engines.

The study covered an extreme case of changes, i.e. changes in both the swept volume, compression and compression ratio (formula 23).

To evaluate the research problem, theoretical and experimental data from the tests of the VW 1.4 TSI internal combustion engine carried out at the Department of Vehicle Engineering of the Wroclaw University of Science and Technology - **Figure 7**. The next data were used from the tests on the chassis dynamometer of vehicles equipped with 1.8 T and 2.0 TDi engines - **Figure 8**.

The research data constituting the boundary conditions for the evaluation of the 1.5 TFSI engine were obtained from the literature [40].

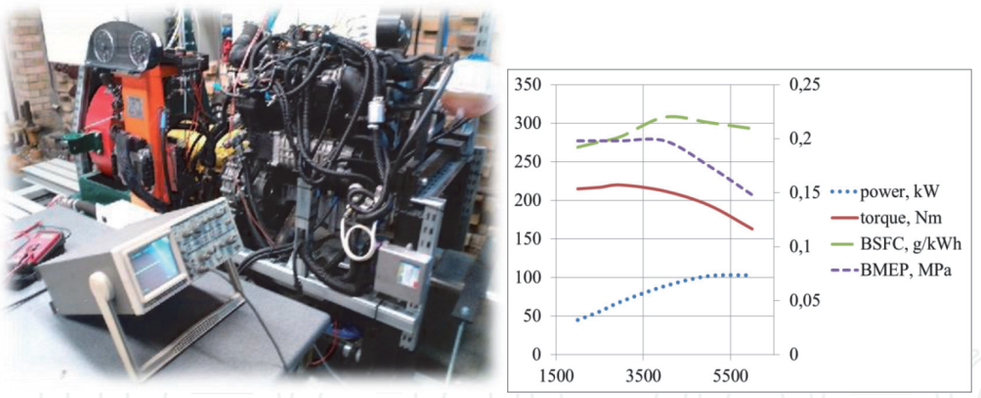


Figure 7.
VW 1.4 dm³ engine on the test stand [39].

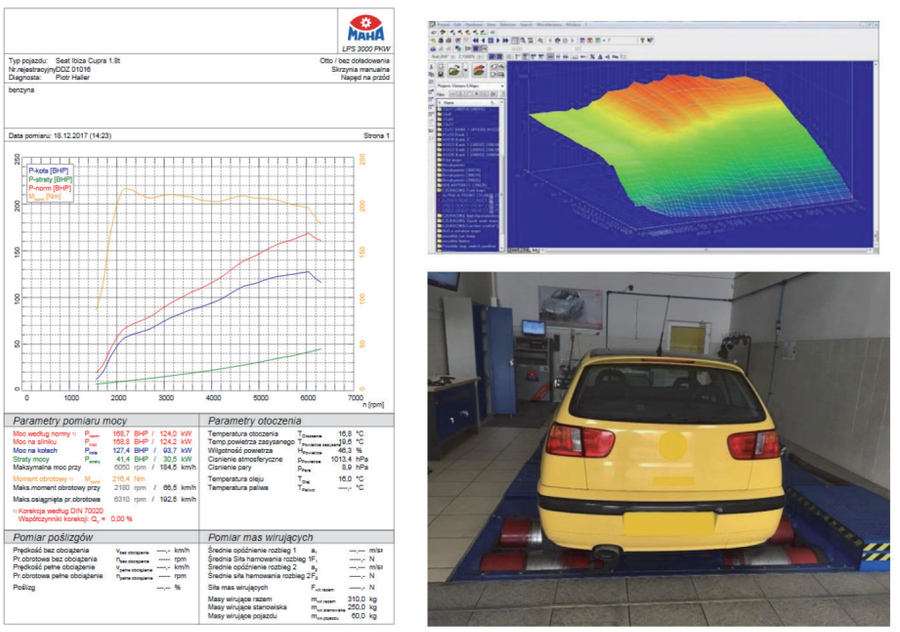


Figure 8.
Tested vehicle with a 1.8 T engine on a chassis dynamometer.

The downsizing/rightsizing indexes according to formula (12) for the cascade of changes of the swept volume are as follows:

- 2.0 dm^3 na 1.8 dm^3 W_d = 0.09
- 2.0 dm^3 na 1.5 dm^3 W_d = 0.25
- 2.0 dm^3 na 1.4 dm^3 W_d = 0.29

For each case, apart from the factory version, theoretical changes related to the behavior of the W_d index with different coefficients A and B, taken from the matrix of changes - **Figure 2**, were considered.

In this way, a package of variables was obtained and analyzed - **Table 1**.

It is worth noting that in the case of the 1.4 dm^3 engine, in which downsizing/rightsizing according to the form "cylinder version" (A = 1) was intended, the rule of mutual relation of the diameter and stroke of the piston, which should be in the range (0.77–1.30) - as discussed above. Hence the decision to change the relation to the closest unity to A = 0.97.

Engines	S	A	S_d	D	B	D_d	W_d	D/S	D_d/S_d	Remarks
dm^3	mm	—	mm	mm	—	mm	—	—	—	
2.0	92.80	—	—	82.50	—	—	0	0.89	—	base
1.8		0.91	84.10		1.00	82.50	0.090		0.98	Factory-1.8_1
1.8		1.00	92.80		0.955	78.80	0.088		0.85	Test-1.8_2
1.8		0.97	90.00		0.97	80.00	0.087		0.89	Test-1.8_3
1.5		0.93	85.9		0.90	74.50	0.247		0.87	Factory-1.5_1
1.5		0.75	69.60		1.00	82.5	0.250		1.19	Test-1.5_2
1.5		1.00	92.80		0.87	71.50	0.243		0.77	Test-1.5_3
1.4		0.82	75.60		0.93	76.50	0.291		1.01	Factory-1.4_1
1.4		1.00	92.80		0.84	69.30	0.294		0.75	Does not meet $0.77 \leq D/S \leq 1.30$
1.4		0.97	90.00		0.855	70.50	0.291		0.78	Test-1.4_2
1.4		0.71	65.00		1.00	82.50	0.290		1.25	Test-1.4-3

Table 1.
The stroke and cylinder diameter values and the corresponding coefficients define the downsizing/rightsizing area.

The values of the A and B coefficients taken for the assessment filled successive values of the downsizing/rightsizing W_d index, ensuring their invariability within a given cylinder volume. The remaining data, filling the form of the formula for the efficiency of the comparative cycle with the equivalent volume (formula 23) and enabling the evaluation of the engine performance indicators, were obtained from the above-mentioned laboratory tests.

4. Discussion of the results

Typical operating indicators of engine work were assessed together with parameters of the thermodynamic cycle, including the efficiency of the generalized work cycle. The obtained data are presented in the form of relative changes, i.e. as a percentage of the data for the base engine 2.0 dm^3 - **Tables 2–4**.

The data contained in **Table 2** refer to the 1.8 dm^3 engine and confirm the correctness of the downsizing idea due to the reduction in fuel consumption by an average of 5%. Thanks to the support systems with supercharging at the forefront and control of the combustion process, even an increase in power of nearly 14% compared to the 2.0 dm^3 unit was achieved.

Greater efficiency was obtained both on the theoretical and useful side. The differences between the efficiency changes η_e and η_t are due to exhaust losses and cooling.

It is worth emphasizing that the change of the coefficients A and B, in such a way that the downsizing index W_d is maintained, did not cause significant differences in the values of all examined parameters and fell within the limits of statistical significance.

The data contained in **Table 3** refer to the 1.5 dm^3 engine and confirm the correctness of the downsizing concept due to the reduction in fuel consumption by an average of nearly 20%. The proposal to reduce the stroke volume by about 25% is close to aggressive downsizing.

Parameter	Manufacturer-2.0	Manufacturer-1.8_1	Test-1.8_2	Test-1.8_3
		% 1.8/2.0	% 1.8/2.0	% 1.8/2.0
ε	10.5	−4.7	−4.7	−4.7
rpm	6000	−8.3	−8.3	−8.3
n_1	1.35	−1.5	+0.4	−1.0
n_2	1.19	0	−0.2	0
T_{max}, K	2706	−0.7	+0.1	−0.5
η_v	0.92	+29.1	+28.9	+29.1
BMEP	1.11	+36.8	+35.9	+36.0
BSFC, g/kWh	264	−5.6	−5.2	−5.0
N_e, kW	110	+13.6	+13.7	+13.7
η_e	0.32	+6.0	+5.5	+5.3
η_t	0.45	+0.7	+0.4	+0.4

Table 2.
*Values of selected engine operating parameters 1.8 dm³ in relation to 2.0 dm³ at different values of the downsizing/rightsizing coefficients A and B (**Table 1**).*

Parameter	Manufacturer-2.0	Manufacturer-1.5_1	Test-1.5_2	Test-1.5_3
		% 1.5/2.0	% 1.5/2.0	% 1.5/2.0
ε	10.5	+19.1	+19.1	+19.1
rpm	6000	−16.7	−16.7	−16.7
n_1	1.35	+9.0	+9.0	+9.7
n_2	1.19	−2.5	−2.5	−2.5
T_{max}, K	2706	+6.6	+6.6	+7.5
η_v	0.92	+26.6	+26.6	+29.7
BMEP	1.11	+54.3	+56.7	+59.4
BSFC, g/kWh	264	−19.7	−20.9	−19.5
N_e, kW	110	+2.9	+2.1	+0.22
η_e	0.32	+24.5	+26.4	+24.2
η_t	0.45	+6.9	+7.2	+6.8

Table 3.
*Values of selected engine operating parameters 1.5 dm³ in relation to 2.0 dm³ at different values of the downsizing/rightsizing coefficients A and B (**Table 1**).*

The approx. 27% increase in volumetric efficiency is due to the boost system and variable valve timing set. The engine power was retained with the seemingly reasonable boost, which resulted in a greater than the 1.8dm^3, but less than 1.4dm^3 increase in BMEP. In the group of tested engines, it is the only engine in which the *downspeeding* concept was applied, changing the maximum value of the engine speed from 6000 to 5000 rpm. There was no significant increase in temperature in the maximum work cycle. Keeping the downsizing/rightsizing index W_d at the level of 0.25, it was shown that the change of coefficients A and B does not cause differentiation of the theoretical work cycle efficiency.

Parameter	Manufacturer-2.0	Manufacturer-1.4_1	Test-1.4_2	Test-1.4_3
		% 1.4/2.0	% 1.4/2.0	% 1.4/2.0
ε	10.5	−4.7	−4.7	−4.7
rpm	6000	0	0	0
n_1	1.35	+7.5	+7.4	+9.6
n_2	1.19	−3.4	−3.4	−2.5
T_{max}, K	2706	+5.0	+5.0	+6.5
η_v	0.92	+38.4	+39.0	+37.8
BMEP	1.11	+62.2	+60.4	+62.0
BSFC, g/kWh	264	−13.7	−12.4	−14.0
N_e, kW	110	+13.6	+13.6	+13.5
η_e	0.32	+15.9	+14.2	+13.5
η_t	0.45	+2.7	+2.7	+2.6

Table 4.
*Values of selected engine operating parameters 1.4 dm³ in relation to 2.0 dm³ at different values of the downsizing/rightsizing coefficients A and B (**Table 1**).*

The data in **Table 4** refer to the 1.4 dm^3 engine and indicate an aggressive downsizing of up to 30%. The expected effect was achieved, i.e. the specific fuel consumption was reduced by an average of 13%, which obviously translates into a reduction in carbon dioxide emissions to the atmosphere. The implementation of support systems for geometric changes resulted in a significant increase in BMEP by over 60%, which may result in a reduction in the durability of engine parts, especially in the area of the piston and crank system.

The differences between the efficiency changes η_e and η_t are due to losses in the exhaust and cooling systems.

The change of coefficients A and B does not significantly affect, and even the differences in values are insignificant, on the tested parameters.

From the point of view of rightsizing, it should be noted a clear relationship between the cycle efficiency and the necessary change in the stroke volume, i.e. one that will correspond to a sustainable approach to design by meeting customer needs and at the same time fulfilling the manufacturer's capabilities.

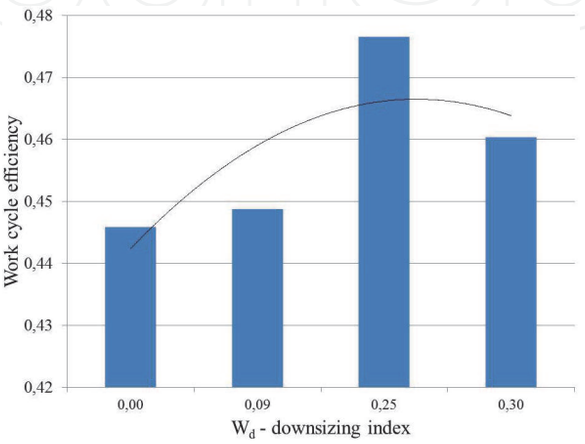


Figure 9.
Changes in the efficiency of the engine work cycle in relation to the downsizing index.

Figure 9 presents the relationship between the cycle efficiency and the downsizing index, which shows that the reduction of the swept volume will be effective up to a certain limit. For the analyzed case, the implementation of an engine with a volume of 1.5 dm^3 instead of 1.4 dm^3 is an example of this.

5. Summary

The problem of changing the displacement of the internal combustion engine is known as downsizing, but recently it has been undergoing a transformation towards rightsizing. It is the result of a new approach to the design and operation process, which assumes balancing the customer's requirements and the manufacturer's capabilities, all in a specific environment, e.g. constantly tightening ecological standards. Anyway, the ecological aspect is the most desirable criterion for assessing the rightsizing concept, which is expressed in the pursuit of reducing fuel consumption and the resulting reduction in carbon dioxide emissions, all for the correct selection of the engine's displacement volume.

A research problem was defined, which is the assessment of the influence of the differences in geometrical changes of the piston stroke and the cylinder diameter, while maintaining the same value of the downsizing index, on the efficiency of the engine work cycle.

To fulfill the aim of the research, the relationship describing the theoretical efficiency of the general reference cycle was modified, in which instead of the stroke volume, substitute coefficients defining changes in the value of the piston's stroke (A) and the cylinder diameter (B) were revealed.

A spectacular case of changes was adopted for the considerations, assuming a change in the swept volume and the accompanying changes in the compression space and compression ratio. The necessary data for the analysis was obtained from laboratory tests and from the literature. There have been repeatedly estimated intermediate quantities defining the efficiency of the engine supported by the obtained engine operation parameters.

The analysis of the results shows that the efficiency of the internal combustion engine cycle is stable, regardless of the A and B coefficients, which determine the geometric changes of the engine displacement volume.

The presence of the limit value of the downsizing/rightsizing index was also demonstrated, at which the highest level of positive change in the circulation efficiency is achieved, corresponding to the sustainability requirements.

In the next steps, the research work must be targeted at detailed on-road exhaust gas toxicity testing of downsizing/rightsizing engines. Due to the significant load on the engine structure, it will also be important to pay attention to the issues of material engineering and tribological processes related to the downsizing/rightsizing concept.

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Nomenclature

A	coefficient of change of piston stroke
B	coefficient of change of cylinder diameter
BMEP = p_e	brake mean effective pressure
BSFC = g_e	brake specific fuel consumption
D	cylinder diameter - input state
D_d	cylinder diameter in the downsized engine
Ge	fuel consumption per hour
L_p	moles index for ambient air
MR	universal gas constant
N_e	useful power
p_o	ambient pressure
rpm = n	engine revolution
S	stroke of the piston - input state
S_d	stroke of the piston in the downsized engine
T_o	ambient temperature
V_{ss}	engine swept volume
W_d	downsizing/rightsizing index
W_u	fuel calorific value
δ	degree of another expansion process
ε	geometric compression ratio
ε_s	effective compression ratio
η_t	theoretical efficiency of the work cycle
κ	isentropic exponent
λ_p	degree of pressure increase during isochoric heat transfer
ρ'	degree of pre-compression when heat is drained at constant pressure
ρ_p	degree of expansion during isobaric heat transfer
ρ_T	degree of expansion during isothermal heat transfer
τ	stroke index (number of strokes)

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