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Review Article

Engine Downsizing; Global Approach to Reduce Emissions: A World-Wide Review

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Abstract

Engine downsizing is a promising method to reduce emissions and fuel consumption of internal combustion engines. The main concept is to reduce engine displacement volume while keeping the needed output characteristics unchanged. The issue has become one of the most current fields of interest in recent years after the International Energy Agency set a target of a 50% reduction in global average emissions by the year 2030. In this review paper, different aspects of researchers' efforts on engine downsizing are configured and, due to overlaps, categorized into five main areas. Each category is discussed thoroughly, and recent works are highlighted. The global attention in these categories, the countries involved and the trend change in the last four years are presented in detail.

Keywords: Internal Combustion Engines; Engine Downsizing; Emissions.

1. Introduction

The long-term goal of the International Energy Agency (IEA) is reported as a 50% reduction in global average emissions by the year 2030 [1]. To improve vehicles' fuel economy and reduce pollutant emissions, some aspects such as policy changes, enhanced technologies, revised fuels, and reduced vehicle/engine size can be considered as effective techniques. Although extensive research is being done, from using alternative or additive fuels [2, 3] to employing Low Temperature Combustion (LTC) [4, 5] for fuel economy enhancement and emission reduction, engine downsizing remains one of the most applicable ways in the automotive industry to meet the IEA 2030 goal.

Engine downsizing: reducing engine displacement volume providing the same operating parameters, is considered as the most effective strategy to improve the efficiency of powertrain [6] and also achieving the aim of limiting pollutants and CO_2[7]. It reduces CO_2 and NOx emissions, engine block weight, and friction loss, besides enhancing fuel economy [8]. Downsized engines are able to produce the same power as right-sized ones, employing supercharger, turbocharger, twin-charging, direct injection (DI), exhaust gas recirculation (EGR) or variable valve timing (VVT).

The idea of downsizing the engines, which means reducing the main dimensions of the engine and reducing the swept volume with mainly the same or higher torque and power of the engine, has been well known since the 1990s [9-11]. The challenges of improving the performance of downsized engines, involving knock and super-knock, electrification, and using electro-mechanical components, were categorized in different review reports. In 2011, engine downsizing

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efforts direction was reported to the spark ignition (SI) engines and also the future of brake mean effective pressure (BMEP) of compression ignition (CI) engines was estimated 30 bar until 2020 [12]. Employing variable geometry turbine in SI downsized engines was studied in 2014 and higher output torque besides less fuel consumption in part load operation and also high speed response in transient operation were reported as its advantages while cost, durability and turbine inlet temperature limitation were noted as its utilization challenges [13]. The trend of downsizing improvement focusing on industrial companies achievements were published by Pielecha et al. [14]. They reported that industrial companies keen on SI engines downsizing more than CI ones. In 2015, the winner of future engine competition, Engine of the year, was introduced as an engine with more than 68 kW/dm^3 specific power, more than 127 Nm/dm^3 specific torque factor and less than 83 $(g/km)/dm^3$ volumetric emission of CO_2 [15]. The most important reasons for employing a supercharger in a SI downsized engine were reported as fuel economy and better response in transient operation [16, 17]. Engine downsizing efforts in European markets started in 2006, and they reduced fuel consumption by 32% until 2015 [18]. After a brief review of using ethanol as an additive, Wang et al. (2017) [19] reported the maximum volumetric percentage of ethanol in fuel for a downsized engine at 63%. Indeed, the review study on employing electric superchargers (ESC) and turbochargers (ETC) for internal combustion engines (ICE) was done by Lee et al. [20].

As published research on engine downsizing has notably increased since the IEA report, this paper has focused on recent four-year studies (2014–2017) to find a vivid division for different aspects. These categories are introduced in the next section. A global distribution of studies and the changes in work quantity in each category are also discussed.

2. Literature Review

Engine downsizing efforts have flourished since 2011 as the IEA 2030 goal has been published. Some published research on this topic from 2014 to 2017 have focused on many different subjects. It is somehow difficult to categorize these studies and recognize the overlaps, but after a deep investigation into these varied areas, a chart has been drawn to show different subjects and their relations as shown in Figure 1. By this determination, all subjects can be categorized into five groups, namely: electrical, base design, engine components, engine performance, and knock and super-knock. Indeed, the overlaps of different groups in each subsection are defined by linking each other. A more detailed investigation is presented in Figure 1.

2.1. Electrical

Using electric instruments, e.g., electric superchargers (ESC), electric turbochargers (ETC), and electrification, is a promising approach to engine downsizing, which has recently been noticed by American, Dutch, and German institutes, and more studies can be devoted to this field in the future. Marinkov et al. (2016) [21] proposed a model to calculate the optimal buffer size providing supercharger demanded power and noted that electrification employing buffers can remove the turbo-lag in engines equipped with turbocharger systems. Furthermore, the challenges of electrification of turbocharger and supercharger systems in downsized engines and hybrid vehicles were investigated by Lee et al. [22]. In 2017, the literature of using ESC and ETC in internal combustion engines (ICE) was studied in a review study [20], and the potential of electric energy recuperation via turbocharger on a downsized direct injection (DI) spark ignition engine was evaluated by Stoffels et al. [23].

2.2. Base Design

Downsized engine base design, all or focusing on one part of an engine, was widely investigated in Europe and USA and it seems research attention is now reducing in this field since some researchers had changed their focus from geometrical downsizing to improve right-size engines performance [24]. A 50% downsized 3-cylinder engine optimal designing was reported by Hancock et al. [25] focusing on design structure and employed technologies and 30% fuel economy and also CO_2 reduction are reported as their optimal design. Concept of using pneumatic hybridization instead of electric hybridization for ultra-downsizing was reported more cost-efficient by Dönitz et al. [26]. The opportunity of a spark ignition engine 40% downsizing employing high octane bio-fuels and cooled EGR was investigated by Splitter and Szybist (2014) [27]. Indeed, the limits of CI engines downsizing were reported as space limitations for injection and combustion processes, the increase of surface-to-volume ratio which gives rise to higher heat losses and limits related to the air management by Payri et al. [28]. Charge cooling with a tracer-based two-line planar laser induced fluorescence (PLIF) technique in an optical gasoline direct injection (GDI) engine was introduced as an idea to increase volumetric efficiency and compression ratio (CR) for downsized engine by Anbari et al. [29]. In addition, Turner et al. [30] have achieved 35% CO_2 reduction designing a 60% downsized engine from a 5L, 8-cylinder V-type Jaguar Land Rover engine. More efficient turbulent flow at intake port in part load operation was achieved using a new design of intake system by Millo et al. [31] while it was not realized at full load. Cooperating of this new design via advancing of inlet valve closing (IVC) and employing turbocharger was introduced as an effective way to improve SI engines performance. Severi et al. (2015) [32] asserted that 20% displacement volume reduction besides providing right-size engine maximum power of studied GDI engine is achievable via 11% piston bore reduction and using both engine boosting and spark advancing, in a numerical investigation. A light duty downsized diesel engine, called z-engine, was developed utilizing homogenous charge compression ignition (HCCI) mode in high load operation by Kuleshov et al. [33] and it is asserted that less NOx emission was produced in this way. The concept of designing a boosted uni-flow scavenged direct injection gasoline engine to achieve more than 50% downsizing is presented by Ma and Zhao [34] for a two stroke engine. Furthermore, friction loss investigation due to employing microgeometry piston bearing [35] and oil pan design for modern downsized engine [36] were studied in 2017.

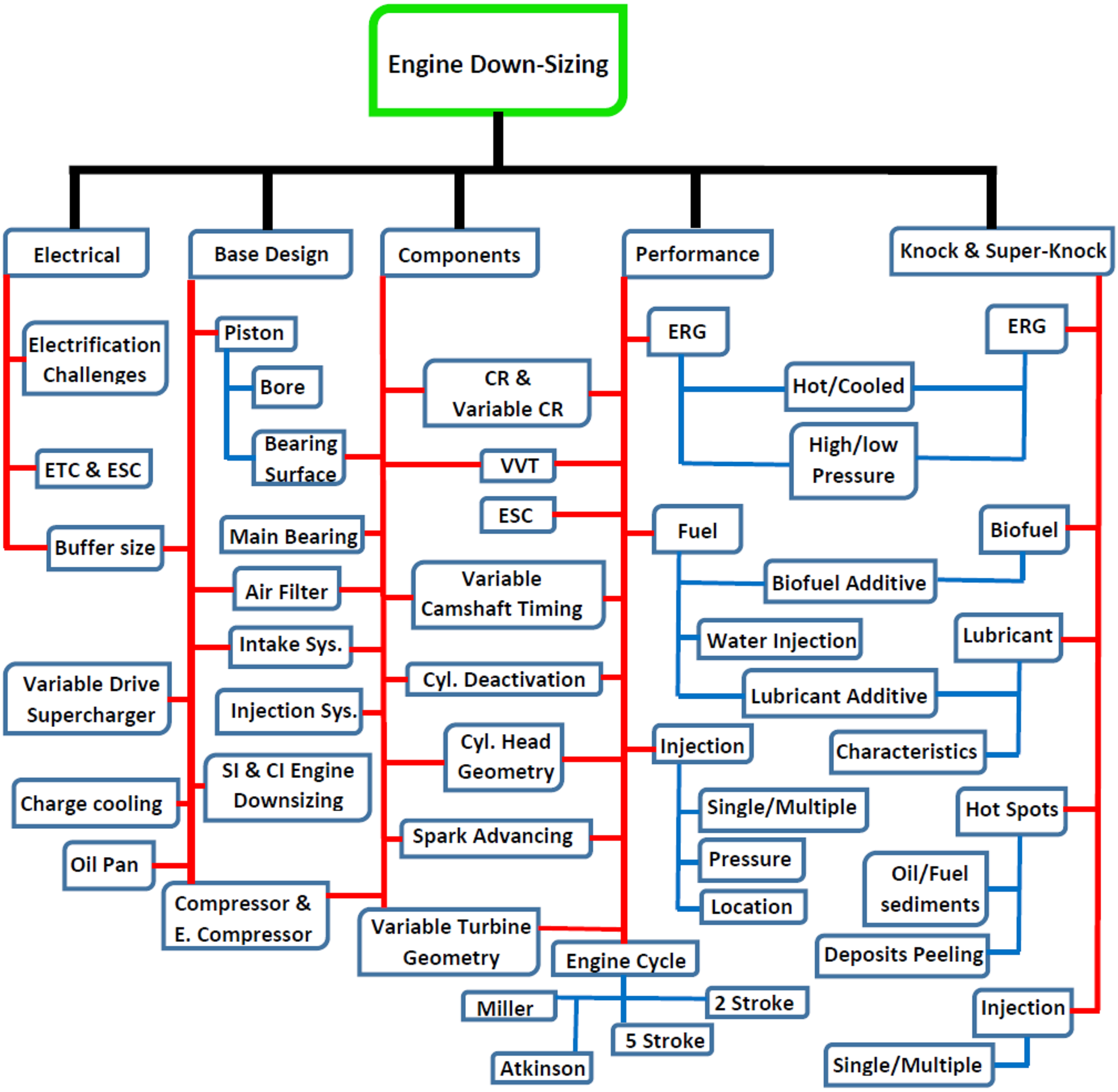

Figure 1. Strategies for downsized engines investigation/improvement

2.3. Engine Components

Downsized engine components, their behavior, and their effects on engine performance are a popular issue, which is being widely investigated in the UK, China, and the United States. Marelli et al. (2014) [37] investigated the pulsating flow performance of a turbocharger compressor generated by the extremely downsized engine intake valves. Piston reinforcement employing titanium or metal–ceramic composites and pressure casting or forging was proposed for heavy downsizing, more than 30%, by Sroka and Dziedzioch [38]. Using turbocharger-supercharger configuration as boosting system was reported more suitable in both fuel economy and performance of the 1.5L diesel engine powered passenger car at all studied operating conditions by Biller et al. (2015) [39]. In addition, different strategies for utilizing boosting devices were investigated by Rastelli et al. [40], and the main cause of downsized engine piston deformation is introduced pressure waves due to the knock by Yao et al. [41]. Employing ESC was proposed for heavy downsizing and achieving excellent fuel economy besides high speed response in transient operating by Bassett et al. (2016) [42, 43]. It is also easier to maintain and has a higher cost than using low and high pressure turbines in a boosting configuration called TRITURBO [44]. Fuel injection systems of previous developed engines were compared with a downsized compressed natural gas (CNG) fueled SI engine provided by Mahle [45], and a 31% reduction was achieved using the variable geometry turbine in the studied engine. Furthermore, a sufficient method of air filter manufacturing based on the minimum pressure drop for downsized engines was presented by Wu et al. [46]. The real load applied to the main bearing of a downsized engine was studied by Matsumoto et al. [47] and it was noted that it is far from the load calculated by the simple known correlation between in-cylinder pressure and main bearing load. Bassett et al. (2017) [48, 49] studied the performance and fuel consumption of a 1.2L 3-cylinder engine equipped with ESC and a 48V lead-carbon battery in different driving cycles. Using a battery was also proposed to troubleshoot the engine speed reduction caused by employing ETC and variable geometry turbines in heavy duty diesel engine downsizing [50]. A high efficiency electric compressor which operates sufficiently at low speed was designed by Wang et al. [51] and a novel boosting system consisting of a turbocharger cooperating via an independent compressor which is manageable by clutch was proposed, achieving better performance in transient operation by Hu et al. [52].

2.4. Knock and Super-knock

Another interested issue on engine downsizing field is knock investigation. Along with all the known reasons for engine knock such as hot spots and oil droplet formation/deposits, operating near the knock condition due to high compression ratio and/or charge boosted pressure brings intense knock [53], called super-knock, especially in low speed operating condition for downsized engines. Charge ignition before the spark time in low speed operation is also called low speed pre-ignition (LSPI) which may cause serious damages to engine. Researchers' efforts to investigate and reduce downsized engines knock and super-knock can be categorized in five groups namely; studying EGR, bio-fuel, lubricant, hot spot and injection.

Fontanesi et al. [54] studied knock using auto-regressive of experimental in-cylinder pressure data and also 1D/3D simulation of a downsized engine combustion in 2014. The main source of LSPI was introduced the auto-ignition of in-cylinder separated gas phases in a comparative study of a downsized SI and two downsized CI engines [55] and deposits peeling from combustion chamber walls were identified as a new mechanism causing LSPI by Okada et al. [56]. In addition, using lubricant oil as a fuel additive to charge ignition tendency and super-knock impact reduction was proposed by Welling et al. [57] and also LSPI caused by engine oil and/or heavy ends of gasoline local igniting was investigated in a separated study [58]. The effects of pressure wave caused by charge auto-ignition on ignition delay and pressure fluctuations in a hydrogen fueled downsized engine were evaluated numerically by Wei et al. [59]. Advancing ignition timing [60] and large size solid carbon particle [61] were reported as other reasons of super-knock and excess air coefficient, engine coolant temperature and valve timing were introduced as important parameters on LSPI [62] in 2015. Lubricant oil formulation is another effective parameter on LSPI and using calcium [63], magnesium [64] and aromatic species [65] as additives of lubricant have strong effect on the frequency of LSPI in which knock can be prevented using these species. Furthermore, using lubricant oils with calcium compounds as fuel additives [66] or injection them in warm inlet air [67] can increase ignition delay and decrease LSPI while lubricant with magnesium has no effects on ignition delay. The effects of early and late intake valve closures on knock were also investigated by Luisi et al. [68] and it was reported that late IVC has positive effects in full load and high speed operation while there is no effect for early IVC.

In 2017, knock and super-knock was considered in other views; Pan et al. [69] investigated it via 3D large eddy simulation (LES) coupling detailed chemistry solver and asserted that single hot spot makes stronger pressure wave than multi-points auto-ignition. Khosravi et al. [70] investigated knock due to hot spots via multi-zone thermodynamic model and computational knock index was introduced in a 3D RANS simulation to define knock limits by Chevillard et al. [71]. Linear trend between cycle to cycle variation and burn rate was reported by Chen et al. [72] while no significant change in knock limit due to coolant flow rate and temperature was achieved by Asif et al. [73]. Szybist et al. [74] also studied the effect of employing cooled EGR at high load operation and reported that it is less effective than low load operation due to polytrophic coefficient enhancement by adding EGR. Knock impact reduction is reported increasing ethanol percentage as an additive due to its sufficient latent heat of vaporization [75] while more knock is occurred due to vaporization rate reduction [76]. In addition, split injection cooperating Miller cycle was employed to knock resistant enhancement in a downsized engine in 2018 [77]. Pressure wave caused by two hot spots was also evaluated by Wei et al. [78] for primary reference fuel (PRF) and it was noted that in the same initial condition, the distance for detonation formation within PRF0 air mixture is shorter than PRF40.

2.5. Engine Performance

The most interested field of research on engine downsizing is engine performance analysis due to the change on engine different parameters. More than half of studied works are devoted to this category and they are divided into four main sections namely; performance analysis due to EGR, fuels, injection strategy and engine base cycle.

EGR

Different strategies of employing EGR are studied in literature to achieve less emission besides increasing downsized engine operating limit. These strategies are namely using cooled or hot and high or low pressure EGR.

Cairns et al. [79] using cooled EGR achieved 3% fuel saving besides 10% CO_2 emission reduction at part load condition of a turbocharged SI engine. They also noted that external cooled EGR is more sufficient than internal one and reported that CO_2, CO and HC emissions are reduced by 17%, 70% and 80% respectively, using this strategy. Also, 6% to 11% specific fuel consumption (SFC) reduction using EGR and controlling boost pressure and spark timing was reported by Galloni et al. [80] in a downsized gasoline fueled engine investigation. In addition, 3.5% enhancement on thermal efficiency and 9% less fuel consumption was achieved using 25% cooled EGR besides increasing CR from 9.3 to 10.9 in a downsized GDI engine studied by Su et al. [81]. Using low pressure cooled EGR at turbocharge condition, 5% fuel economy improvement was reported by Takaki et al. [82] and less knock tendency at full load operation was reported by Teodosio et al. [83]. Less particular matter (PM) and soot as advantages and liquid water forming at intercooler as disadvantage of employing low pressure EGR were expressed by Luján et al. [84] and 48% soot emission reduction using cooled EGR was reported by Li et al. [85]. Bozza et al. [86] achieved 25% to 30% SFC reduction employing cooled low pressure EGR and port water injection and both low and high pressure cooled EGR effects on engine performance and emission are studied by Shen et al. [87]. They asserted that there is no difference between high and low pressure EGR for combustion process but turbine and compressor performance are affected. Furthermore, high pressure cooled EGR was reported more effective on fuel economy at high load operation while low pressure one was expressed more sufficient at low load operation [88]. Cooled EGR effects on the performance of a downsized GDI engine were studied by Jadhav and Mallikarjuna [89] and 2% and 2.3% enhancement on indicated mean effective pressure (IMEP) and thermal efficiency besides less in-cylinder temperature and NOx emission were reported.

Fuels

Using different fuels to achieve better performance is always an interested field of study for engine researchers. In downsized engine, employing additives to increase knock resistant is always popular.

Remmert et al. (2014) [90] studied the effect of research octane number (RON) between 95 and 112 on a downsized SI engine and reported that RON increasing on 2000 to 3000 rpm can improve 5 to 10 CAD spark timing limitation due to the knock. Jo et al. [91] reported fuels with higher octane number are needed via engine downsizing. In addition, 0.3% reduction in engine efficiency via decreasing methane number from 69 to 64 is reported by Kramer et al. [92] and using fuels with methane index over 60% were reported as suitable alternatives for gasoline in downsized engines [93].

The effect of using lubricant oil as an additive to iso-octane on combustion quality was investigated by Kuti et al. [94] and 54% reduction on ignition delay was reported due to 10% lubricant oil addition. In addition, water injection into the charge is another way of engine efficiency enhancement [95, 96] and it was expressed effective strategy on fuel economy and knock impact [97]. It also improved more than 5% mean effective pressure and 34% thermal efficiency at full load [98]. HC emission and noise reduction due to water direct injection into the combustion chamber was reported by Tornatore et al. [99] and it is expressed that spark time advancing and near the stoichiometry condition operating is possible employing this technology. It is also asserted that NO emission can be increased if spark time is advanced due to higher in-cylinder pressure and temperature.

Alcohols are the most attractive additives employed on engine downsizing which increase fuel knock resistant. Baêta et al. [100] using Brazilian hydrated ethanol achieved 44% efficiency from a 1.4L downsized DI engine. Cho et al. [101] reported 96% PM reduction in part load and cold start operation employing 20% volumetric ethanol in gasoline blend. Optimal fraction of ethanol in dual fuel applications was investigated by Jo et al. [102] and using high octane fuel like E85 was proposed for CR enhancement more than 11.5. In-cylinder flow field and flame development in an ethanol fueled DI engine were studied by Koupaie et al. [103] and the idea of employing anhydrous ethanol was expressed by Martins et al. [104]. In addition, using pure butanol in comparison by gasoline, produced 2% more output torque and power [105] and by employing butanol-gasoline blend, output torque and efficiency in part load operation were increased by 4% [106]. The main achievements of adding ethanol to the gasoline were reported HC and NOx reduction and noticeable PM reduction was obtained using butanol as an additive [107]. The optimum spark times advancing for ethanol-gasoline and butanol-gasoline blends in a downsized SI engine were defined by Scala et al. (2017) [108]. Furthermore, fuel consumption and CO_2 4% to 11% reduction, PM 86% to 99% decrease and noticeable NOx increase were reported using bio-fuels such as soybean methyl ester (SME) and rapeseed methyl ester (RME) in a downsized diesel engine [109].

Injection Strategy

Engine performance, especially emissions, will be affected by the type of fuel injection and charge preparation. PM production due to the port fuel injection (PFI) and DI strategies were studied by Su et al. [110] and more PM in DI mode was observed. Indeed, less fuel consumption and emission reduction via injection pressure enhancement were reported by Hoffmann et al. [111] and 60% and 80% decrease on PM were achieved using dual and triple injection strategies respectively, by Su et al. [112]. Piston wall wetting prevention and less PM were also reported as advantages of early fuel injection by Xu et al. [113].

Engine Base Cycle

In addition to the most of investigated research which focused on 4-stroke Otto and Diesel engines, other engine base cycles were studied in downsized approach. The performance of 2-stroke downsized SI engine was studied by Dalla Nora et al. [114] and less fuel consumption in middle loads and less residual gasses and NOx emission besides higher CO and HC in low intake pressure were achieved. Li et al. [115] changing a 4 cylinder SI engine to the 5-stroke 3 cylinder engine obtained 4% more thermal efficiency and 9% to 26% less fuel consumption. Furthermore, in comparison with Miller cycle, the performance of 5-stroke cycle in high load condition was reported more sufficient and vice versa [116]. Employing Miller cycle 4.7% and 7.4% BSFC reduction at full and low load conditions were obtained by Li et al. [117] and Atkinson cycle effects on ultra-downsized engine performance were also studied by Gheorghiu [118].

Other Studies

The performance of downsized engine is also investigated in other aspects which were illustrated in this section. The effects of engine downsizing on thermal characteristics and performance were studied by Sroka [119] and a numerical tool for fuel consumption map generation was presented to evaluate downsized engine SFC by Alix et al. [120]. In addition, exhaust back pressure was introduce as an effective parameter on PM emission of downsized DI engine and asserted that PM decreases via exhaust back pressure enhancement [121]. The correlation of heat flux due to pressure increase caused by knock in cycle-by-cycle variation was introduced by Mutzke et al. [122] and conjugate heat transfer in cylinder wall of a downsized SI engine was studied by Leguille et al. [123]. Jatana et al. [124] studied the sensitivity of SI combustion on fuel perturbations to obtain a control strategy for operating instability and Tong et al. [125] used an ion current sensor for combustion diagnosis, knock and LSPI detection. The effects of employing variable compression ratio [126], ESC [127], variable crank shaft timing [128] and VVT [129] on performance and emission of downsized engines were evaluated in different research and CI combustion influence from cylinder head geometry was investigated by Li et al. [130]. Using cylinder deactivation technology Millo et al. [131] obtained 30% reduction on pumping losses and cycle-by-cycle combustion variation simulator was presented and its response time for control approaches evaluated by Dulbecco et al. [132].

3. General Review

Extended efforts on the engine downsizing field between 2014 and 2017 were done all over the world, but they concentrated in Europe by 62.5%, according to publications. In Table 1, the contribution proportion of each mainland is reported, and the number of published works from each country is shown in Figure 2. As it is shown in Figure 2, UK had the highest number of published works, and China, Italy, and the USA are seriously focusing on engine downsizing after England. As discussed in previous sections, these efforts can be categorized into five general groups: electrical, base design, engine components, engine performance, and knock and super-knock investigation. The trend of focusing on each group by researchers during the study time is shown in Figure 3. The most popular group of research is on downsized engine performance, and it is growing over time. Knock and super-knock investigations are another popular group, as well as engine components utilizing studies. Base design studies are falling while electrical investigations, electrification, and electric components utilizing new approaches are able to absorb much more research themselves in the future. As it is impossible to divide some research into separate groups, there are overlaps between almost all groups, which are shown besides the proportion of each group in studied works in Figure 4.

Table 1. Contribution proportion of world universities\institutes among studied works between 2014 and 2017

Continent	Contribution proportion
Europe	62.5%
Asia	23%
America	14%
Oceania	0.5%

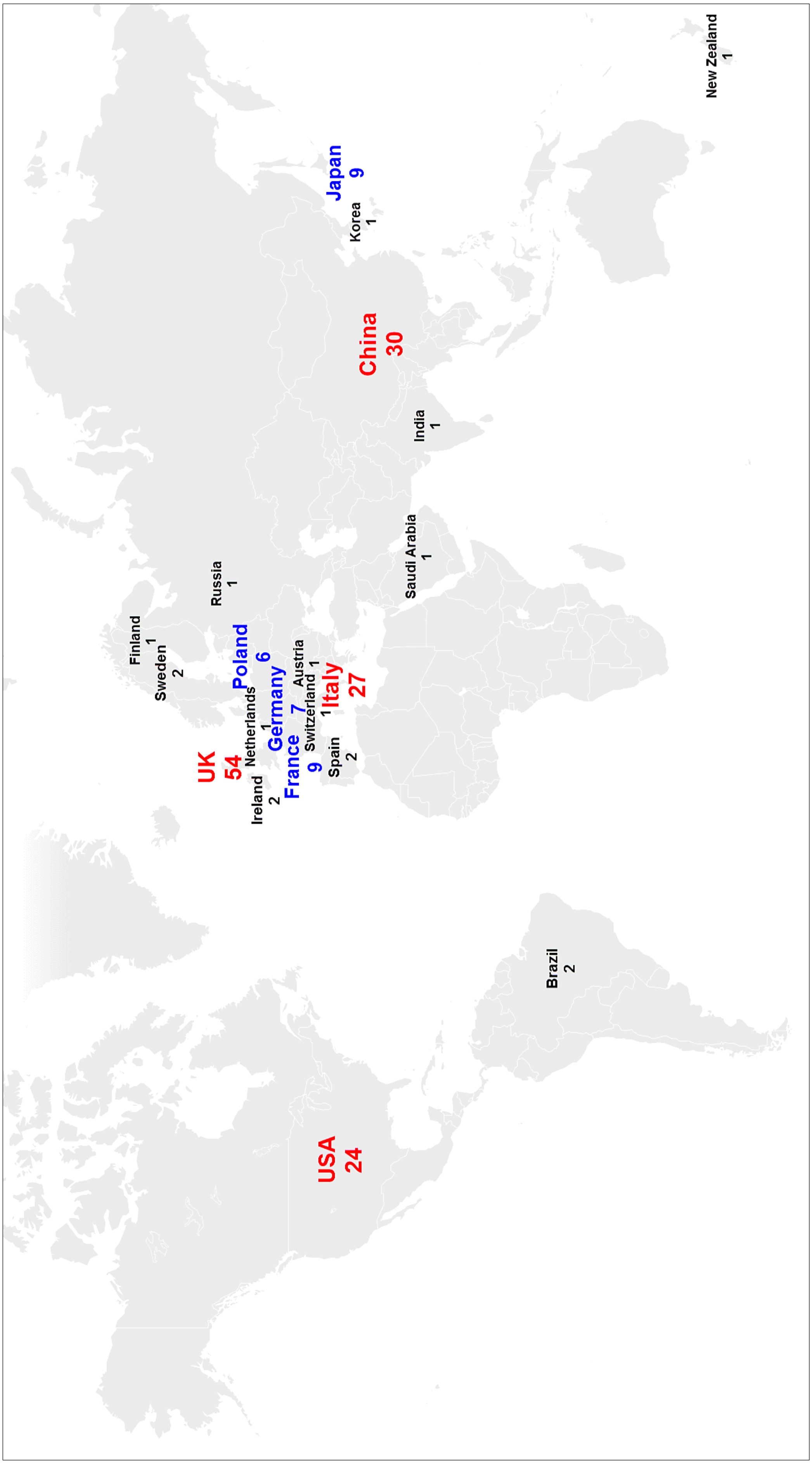

Figure 2. International published works from each country between 2014 and 2017

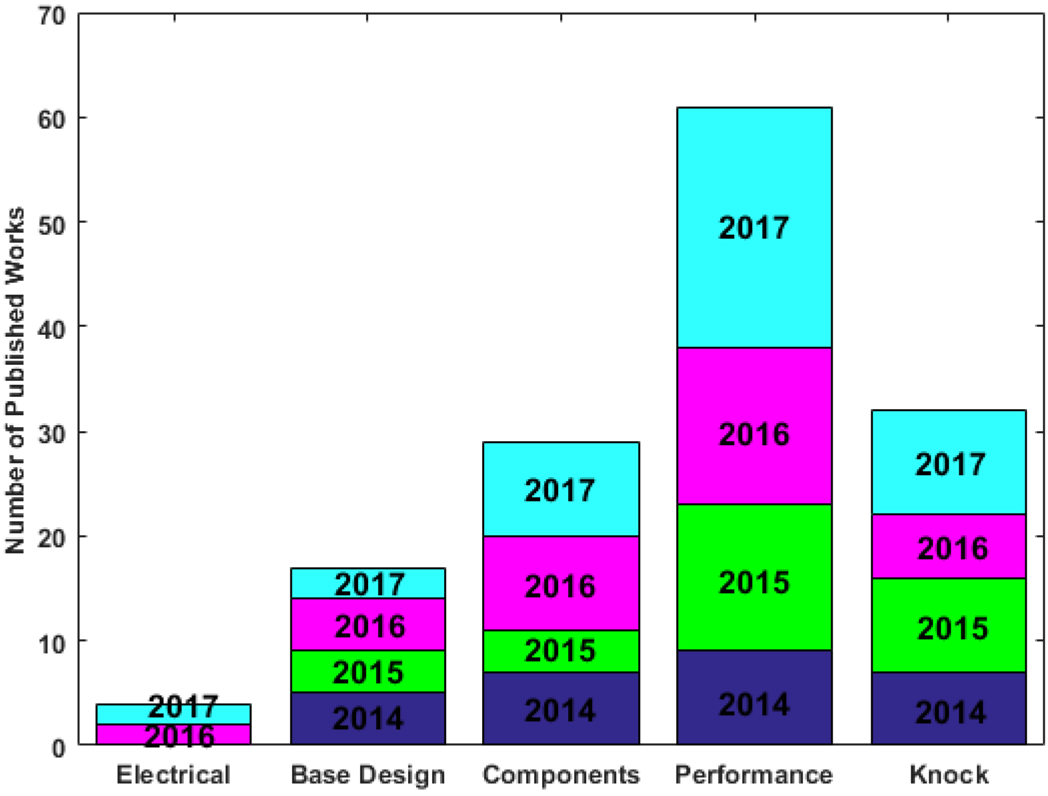

Figure 3. Trend of focusing on different fields of engine downsizing

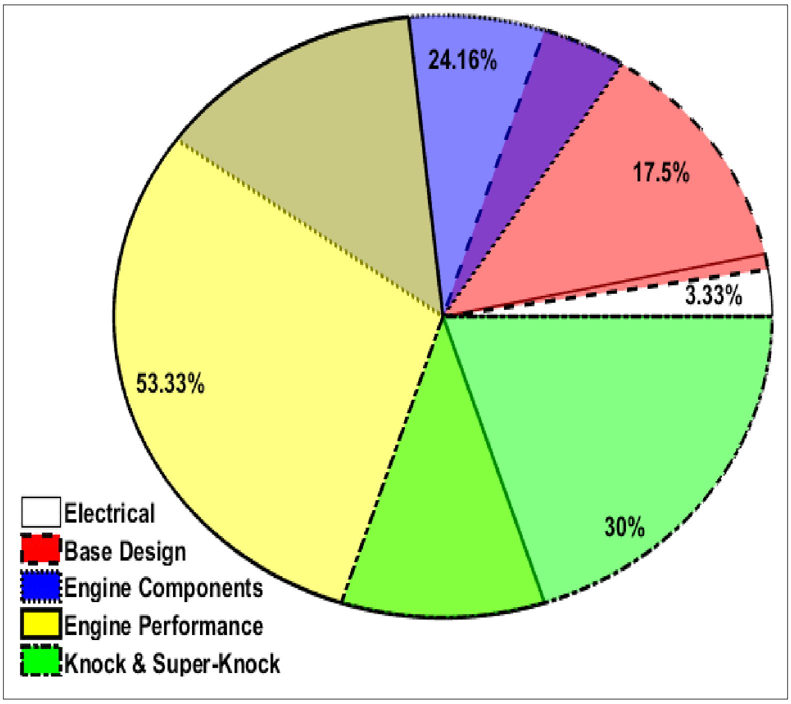

Figure 4. The overlaps and proportion of each field in engine downsizing published studies

4. Research Direction of Top Countries on Engine Downsizing

As it is obvious from Figure 2, four top countries in engine downsizing are, namely, the UK, China, Italy, and the USA. Most of the focus of all four countries was on engine performance, with 38.3%, 47.5%, 52%, and 28.1% of their published works, respectively. The UK focused on engine components and base design after engine performance was investigated by 25% and 21.9%, while China and Italy tried to study knock and super-knock more than other fields. As it is seen in Figure 5, the USA is the only country that started studying electrification and has a more uniform distribution in different groups of engine downsizing.

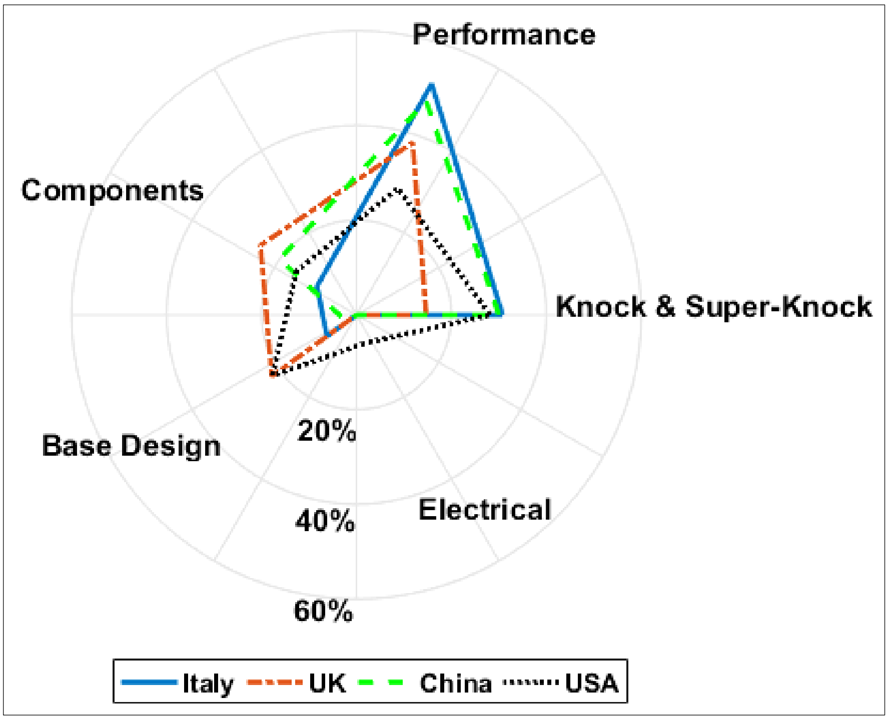

Figure 5. Research distributions of top countries on engine downsizing

5. Conclusions

In this paper, recent efforts on internal combustion engine downsizing are reviewed. Different fields of interest are mapped and their connections and overlaps are illustrated. The total results of this investigation can be mentioned as:

- Different subjects of research on engine downsizing can be categorized into five distinct groups: electrical, base design, engine components, engine performance, and knock and super-knock.
- Electrical: Using electric instruments, e.g., electric supercharger (ESC), electric turbocharger (ETC), and electrification, is an accepted field to enhance engine output power/torque while displacement volume is decreased.
- Electrical: Using electric instruments, e.g., electric supercharger (ESC), electric turbocharger (ETC), and electrification, is an accepted field to enhance engine output power/torque while displacement volume is decreased.
- Engine Components: Downsized engine components, their behavior, and also their effects on engine performance are popular issues.
- Knock and Super-knock: Almost all suggested methods for keeping engine output power/torque constant while downsizing would increase the probability of knock occurrence, so dealing with this phenomenon is an important field of interest.
- Engine Performance: The most interesting field of research on engine downsizing is engine performance analysis due to the change in engine parameters. More than half of the studied works are devoted to this category, and they are divided into four main sections, namely: performance analysis due to EGR, fuels, injection strategy, and engine base cycle.
- Europa has the most interest in the engine downsizing field. The UK and Italy are actually the leaders. Except in the electrical field, this review shows that they have an almost uniform distribution of work in the introduced categories.
- The main efforts in Asia are focused on China and Japan.
- The USA has the most interest in electrical fields.
- As attention to base design has decreased in recent years, engine components and performance studies are growing notably.
- Pretending Knock and Super-knock are always a discussing field.

6. Declarations

6.1. Author Contributions

Conceptualization, M.M.N. and O.J.; methodology, M.M.N. and O.J.; software, M.M.N.; validation, O.J.; formal analysis, M.M.N.; investigation, O.J.; resources, M.M.N.; data curation, M.M.N.; writing—original draft preparation, M.M.N.; writing—review and editing, O.J.; visualization, M.M.N.; supervision, O.J., R.S. and K.N.; project administration, O.J. All authors have read and agreed to the published version of the manuscript.

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6.4. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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