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Diesel engine downsizing with application of biofuels

Xian Mian Tan, Ulugbek Azimov

Department of Mechanical and Construction Engineering, University of Northumbria
Newcastle upon Tyne, NE1 8ST, United Kingdom.

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Abstract
In this study, we have developed an optimization procedure for diesel engine downsizing with application of biofuels. The analysis was performed using the specialist thermodynamic software to simulate combustion and emission characteristics of an internal combustion engine. A JCB 165 kW Diesel Max commercial nonroad diesel engine has been selected for the project. The performance characteristics of this engine were set as reference. The results for the original engine and downsized engine were compared. The engine performance and emission characteristics with diesel fuel, different blends of soybean methyl ester (SME) and rapeseed methyl ester (RME) have been investigated. The obtained results showed that it was possible to achieve equal level of break power and torque for 50%-downsized engine as compared with those of the original engine. The results over different engine speeds and loads showed around 4-11% reduction range in fuel consumption, 4-11% reduction range in CO_2 emissions and about 86-99% reduction range in PM emissions. However, the NOx emissions significantly increased. Further to decrease NOx emission level the exhaust gas recirculation (EGR) was applied.

Keywords: Engine downsizing; Multiparametric optimization; Biodiesel; Engine performance; Engine emissions.

1. Introduction
Engine downsizing can result in lower fuel consumption, lower exhaust gas emission and reduce the costs of the engine. A nonroad diesel engine [1] was selected because these types of engines are widely used in the application of construction and mining machinery, locomotives, electric power generation systems, marine, industrial and agricultural equipment. In such applications, the engine combustion will lead to air pollution and CO_2 emissions, and consequently to global warming. Therefore, engine manufacturers nowadays are trying hard to improve the fuel economy while trying to meet emission standards by increasing the engine boost level [2]. Engine downsizing allows reducing the engine displacement and maintaining the same or higher indicated mean effective pressure (IMEP) by heavy boosting the engine [3]. The engine downsizing allows the preservation of both the break power and torque of the engine without increasing the size of the engine, conversely the ability to decrease the engine size while maintaining engine power at the same level as the larger equivalent [4]. As a result, this will lead to mechanical and thermal loss reductions, the lower weight of the engine, which results in a vehicle's lower weight and will lead to lower fuel consumption and reduced material cost of the engine.

Experiments performed by Turner et al. [5] have showed that engine downsizing has led to significant reduction in fuel consumption and CO_2 emissions. The results showed that in order to achieve the same level of performance as the larger-displacement engine, a higher boost pressure would be required.
Previously the engine downsizing was mostly performed for petrol engines and not many results are available for diesel engines. Ecker et al. [6] showed that the 3-cylinder engine architecture is the simplest, most compact and the highest fuel-efficient. Saulnier and Guilain [7] indicated that steady state performance can be reached by several turbocharger matchings whereas transient performance needs a real optimization.
In this study, we have made attempts to downsize a commercial diesel engine. A computational modelling tool was used to analyze engine performance and emission characteristics. Multiparametric optimization was performed allowing to alter the engine compression ratio, injector nozzle diameter, fuel injection duration, injection timing, injection pressure, intake and exhaust valves opening and closing. Exhaust gas emission level produced by the downsized engine were then compared to that of the European emission standards. The European Union has made a statement that by the year of 2020 it is required to have 10% of the transport fuel in every EU country to be produced from the renewable sources such as biofuels [8]. Therefore, in this study we have also conducted analysis using soy methyl ester and rapeseed methyl ester biodiesel fuels in downsized engine.

2. Theory and modelling

In this project we have used full cycle thermodynamic engine simulation programme – Diesel-RK [9]. The program can be used for modelling direct injection diesel engines, spark ignition petrol/gas engines, dual fuel engines and opposed piston engines. The typical applications include engine performance predictions, analysis and optimization of combustion, emissions, valve timing, EGR system, turbocharger, fuel injection system, piston bowl shape, and conversion of diesel engine into gas engine. Diesel-RK has the fuel spray visualization tool, multiparametric and multidimensional optimization tool and 1D & 2D parametric procedures. The program includes a RK-model that is a multi-zone diesel fuel spray mixture formation and combustion model, which takes into account [10]:

- Piston bowl shape - any geometrical shapes can be specified and saved;
- Different swirl profiles and swirl intensity;
- Sprayer location - central, non-central, side injection, few injectors;
- Number, diameter and direction of injector nozzles,
- Fuel properties, including biofuels and blends of biofuels with diesel oil,
- Shape of injection profile including multiple injections.

2.1 Multiparametric optimization

As mentioned earlier, multiparametric optimization is one of the advanced features in Diesel-RK. The procedure of optimization uses the engine's mathematical model together with the specified goal function and restrictions to find a set of optimal design parameters.

Goal function

The efficiency parameters of an engine or its separate processes can be included in a goal [9]:

$$Z_j = Z_j(X_k) \tag{1}$$

where: Z_j is a function of several variables.
Since the main aim of this project was the reduction of fuel consumption and exhaust gas emissions in biodiesel fuelled downsized engine, the goal function for the optimization analysis was set for the specific fuel consumption. In addition, the total emission level was evaluated by a complex emission parameter Summary of Emissions (SE). It is stated that the complex of air pollutants is a sum of particulate matter (PM) and nitrogen oxides (NOx) emissions and can be calculated as:

$$SE = C_{PM}\frac{PM}{0.15} + C_{NO}\frac{NO_x}{7} \tag{2}$$

where: C_{PM}=0.5, is the empiric line factor for Particulate Matter emission, C_{NO}=1, is the empiric line factor for Nitrogen Oxides emission

Independent variables

The set of design engine parameters form the vector of independent variables, X_k and it is in the restricted solutions area [9]:

$$X_{k\min} < X_k < X_{k\max} \tag{3}$$

In this project, there are six engine parameters selected as the variables for the optimization:

- X_1 is intake and exhaust valve timing (opening/closing),
- X_2 is compression ratio,
- X_3 is injector nozzle diameter,
- X_4 is injection timing,
- X_5 is injection duration,
- X_6 is EGR rate.

With these variables, the goal function becomes:

$$Z_j = Z_j(X_1, X_2, X_3, X_4, X_5, X_6) \tag{4}$$

Restrictions

Restrictions are the parameters that limit the optimal search region while searching the solution in the pool of engine parameters:

$$Y_i = Y_i(X_k) \tag{5}$$

For example, in this case the restricting parameters will be: Y_1 is power, Y_2 is specific fuel consumption (SFC) and Y_3 is volumetric efficiency. To search for an optimum of function $Z_j(X_k)$, the following restrictions have to be fulfilled:

$$Y_{i\min} < Y_i(X_k) < Y_{i\max} \tag{6}$$

Generally, the goal function is a sum of Z_j, X_k and Y_i [9]:

$$F = C_{zj} \cdot \overline{Z}_j + \sum_{i=1}^{n} (C_{yi} \cdot \Delta \overline{Y}_i^2) + \sum_{k=1}^{m} (C_{xk} \cdot \Delta \overline{X}_k^2) \tag{7}$$

where: C_{zj} is a line factor (influence coefficient) of optimized ICE parameter Z_j included into goal function; $\overline{Z}_j = Z_j / Z_{j\mathrm{mean}}$ is a relative ICE parameter Z_j related to its mean average value (e.g. Power, SFC, NOx emission, etc.); C_{yi} is a penalty factor for leaving permitted area of Y_i;

$$\Delta\overline{Y_i} = \begin{cases} \dfrac{Y_i - Y_{i\min}}{Y_{i\,\text{mean}}}, & IF \;\; Y_i < Y_{i\min} \\ 0 \quad , & IF \;\; Y_{i\min} \le Y_i \le Y_{i\max} \\ \dfrac{Y_i - Y_{i\max}}{Y_{i\,\text{mean}}}, & IF \;\; Y_i > Y_{i\max} \end{cases} \quad \text{is a related value of } Y_i; \tag{8}$$

C_{xk} is a penalty factor for leaving permitted area of X_k;

$$\Delta\overline{X}_k = \begin{cases} \dfrac{X_k - X_{k\min}}{X_{k\,\text{mean}}}, & IF \;\; X_k < X_{k\min} \\ 0 \quad , & IF \;\; X_{k\min} \le X_k \le X_{k\max} \\ \dfrac{X_k - X_{k\max}}{X_{k\,\text{mean}}}, & IF \;\; X_k > X_{k\max} \end{cases} \text{is a related value of } X_k \tag{9}$$

Mean values of explanatory variables $X_{k\,\text{mean}}$ and restrictions $Y_{i\,\text{mean}}$ as well as penalty factors of X_k are set by the program. Specification of penalty factors for restrictions C_{yi}; maximum and minimum borders for restrictions $Y_{i\min}$, $Y_{i\max}$ and explanatory variables $X_{i\min}$, $X_{i\max}$ as well as goal function Z_j has to be made by user in the pre-processor of the program [9].

2.2 Algorithm selection

Unfortunately, the theory of nonlinear programming does not answer the question which method is better to solve the multiparametric optimisation problem and a researcher has to be guided by his/her own experience of solving problem while selecting optimisation algorithm. Each algorithm allows finding solutions of optimization problems with different efficiency. For example, Monte-Carlo method is preferred to be used when the optimization problem is posed with a large number of independent variables and it is advisable to set a large number of iterations up to 1000. Due to the restricted power, specific fuel consumption and volumetric efficiency set in this case, the expected optimum will not be far from the starting point, and hence a zero-order optimization method was used. However, it is advised that the first-order method be used in the case when expected optimum is far from the starting point.

As categorized under zero-order methods - on-coordinates descent method, deformable polyhedron method, Powell method and Rosenbrock’s method, these four methods were used to perform multiparametric optimization. The deformable polyhedron method failed to find a local optimum it did not converge and hence caused errors during optimization process. On-coordinates descent method and the Powell method were not preferred because the optimization results showed the exceeding values for restricted parameters. Rosenbrock’s method was the only method that provided optimization results by keeping the parameters within the restricted range. Rosenbrock’s method [11] proceeds by a series of stages and each stage consists of a number of exploratory searches along a set of directions. The directions are fixed for the given stage and updated from stage to stage for the make use of information obtained about the objective. In the first stage, Rosenbrock’s method starts with the search of coordinate directions. It conducts searches of the directions by cycling over each in turn and then moving to new iterations that produce successful steps. The process continues until there has been at least one successful and one unsuccessful step in each search direction, and the current stage terminates after that. For the next stage, Rosenbrock’s method rotates the set of directions instead of repeating the search process at the same orthogonal vectors, to seize information about the objective validated during the early course of action. Rosenbrock’s method imposes the condition that the set of search directions always be *n* dimensional so that the set of vectors remains independent. The function is defined as:

$$f(x, y) = (a - x)^2 + b\left(y - x^2\right)^2 \tag{10}$$

After a few preliminary simulations were conducted, the number of cylinders were reduced from 6 to 4. The diameter and length of the cylinder bore and stroke were reduced to lower the displacement of the engine. A higher boost pressure, injection pressure and cycle fuel mass were applied to the downsized engine to achieve the same level of brake power and torque as the reference engine. The limits and restrictions of the level of downsizing for the reference engine was studied. The downsized engine then has been optimized to achieve better fuel consumption and lower exhaust gas emissions.

3. Computational setup

For the optimization process the specific fuel consumption (SFC) was set as a goal function. The variables such as engine compression ratio, fuel injector nozzle diameter, injection duration, injection timing, intake and exhaust valve opening, intake and exhaust valve closing were set as independent. The restrictions were set for the total engine power, the average piston crown temperature and volumetric efficiency. The engine specification is listed in Table 1. The properties for SME B20, B40, B100 fuel blends were used those in the Diesel-RK fuel library and the RME B100 properties were taken from a Buyukkaya [12]. The fuel properties are listed in Table 2.

Table 1. Specification of engine.

Engine Model	JCB Diesel Max TCAE-165 kW
Engine Type	Diesel DI, 4-Stroke
No. of Cylinders	6
Bore	106
Stroke	135
Displacement	7.2L
Compression Ratio	16.9: 1
Maximum Power	165 kW @ 2000 RPM
Maximum Torque	1000 Nm @ 1500 RPM

Table 2. Properties of diesel fuel and the blends of biodiesel.

Property	Diesel No. 2	SME B20	SME B40	SME B100	RME B100
C mass fraction	87	84.96	82.97	77.31	78
H mass fraction	12.6	12.45	12.3	11.88	13.5
O mass fraction	0.4	2.591	4.73	10.81	8.5
Density @ 323K (kg/m^3)	830	841	852	885	874
Viscosity @ 323K (Pa.s)	0.003	0.003343	0.003677	0.00463	0.00692
Calorific value (MJ/kg)	42.5	41.18	39.89	36.22	37.1
Cetane number	48	48.68	49.37	51.3	39
Specific heat of vaporization (kJ/kg)	250	265.8	281.2	325	325

4. Results and discussion

As shown in Figure 1, the brake power for the reference and 50%-downsized engine were matching. However, for the biodiesel blends of SME20, SME40, SME100 and RME100, the results show lower engine performance. This is because biodiesel has less energy per unit volume compared to that of diesel fuel. For biodiesel SME20, SME40, SME100 and RME100 the reduction in performance is in the range of 1-16 % at the range of 900-2000 rpm compared to that of 50%-downsized engine fueled with diesel. Experiments performed by Murat [13] showed that for an engine that operates with biodiesel fuel the lower engine performance in the break power is achieved compared to an engine operating with diesel fuel due to lower heating value of biodiesel fuel. The results of brake power for reference manufacturer's engine, 50%-downsized engine with diesel fuel and 50%-downsized engine with blends of biodiesel at each rpm are summarized in Table 3.

Figure 2 shows that the torque for the 50%-downsized engine with diesel fuel increases about 1% at 1200 rpm. At the other rpm conditions the engine shows the same performance level as that of the reference engine. For 50%-downsized engine with biodiesel SME20, SME40, SME100 and RME100, the torque is about 2-4%, 4-6%, 12-15% and 11-14% lower respectively in a range of 900-2000 rpm compared to that of the 50%-downsized engine fueled with diesel. Murat [13] conducted experiments with biodiesel fuel and showed that an engine fueled with biodiesel has lower torque compared to the engine fueled with diesel due to lower heating value of biodiesel fuel. The results of engine torque at different rpm conditions are summarized in Table 4.

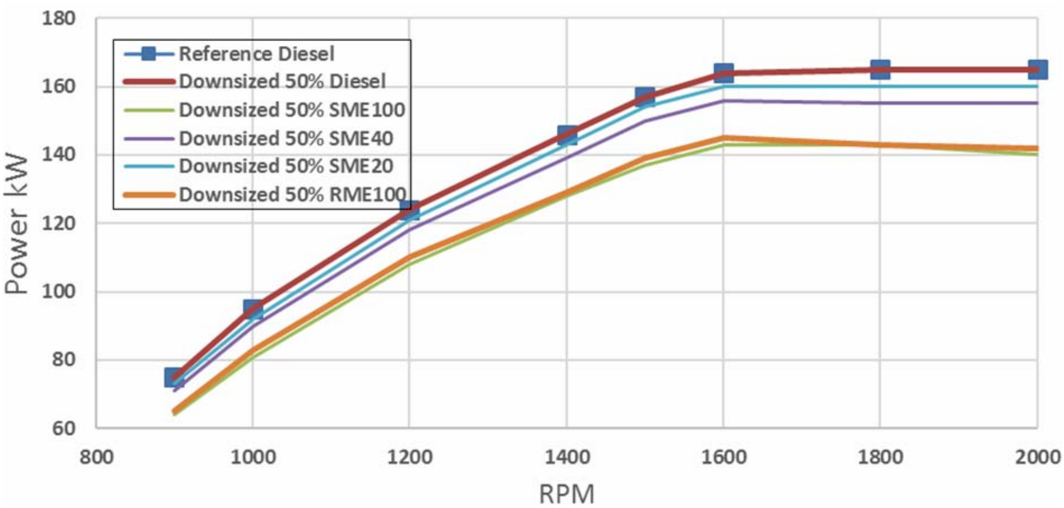


Figure 1. Results of engine break power.

Table 3. Summary table of the brake power.

Brake Power (kW)						
RPM	Reference Diesel	Downsized 50% Diesel	Downsized 50% SME20	Downsized 50% SME40	Downsized 50% SME100	Downsized 50% RME100
900	75	75	73	71	64	65
1000	95	95	92	90	81	83
1200	124	124	121	118	108	110
1400	146	146	143	139	128	129
1500	157	157	154	150	137	139
1600	164	164	160	156	143	145
1800	165	165	160	155	143	143
2000	165	165	160	155	140	142

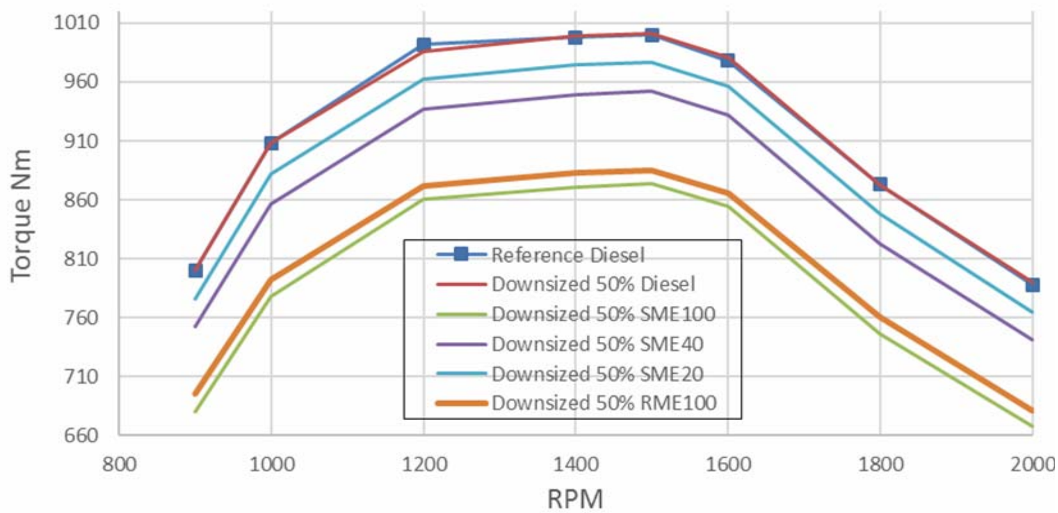


Figure 2. Results of engine torque.

Table 4. Summary table of engine torque.

	Torque (Nm)					
RPM	Reference Diesel	Downsized 50% Diesel	Downsized 50% SME20	Downsized 50% SME40	Downsized 50% SME100	Downsized 50% RME100
900	800	800	776	752	680	695
1000	908	908	882	856	778	792
1200	992	986	962	937	860	872
1400	998	999	975	949	871	883
1500	1000	1001	977	952	874	885
1600	978	981	956	932	854	866
1800	873	873	848	823	746	760
2000	788	790	765	741	668	681

Figure 3 shows that for the 50%-downsized engine with biodiesel SME20, SME40, SME100 and RME100 BSFC increases 2-4%, 5-7%, 14-19% and 13-16%, respectively, in a range of 900-2000 rpm compared to that of the 50%-downsized engine fueled with diesel. Some researchers had confirmed that BSFC increased when biodiesel was used [13, 14]. The increase of BSFC is attributed to the collective outcomes of the higher fuel density, lower break power, torque and higher fuel consumption due to lower heating value of the biodiesel compared to the diesel fuel. The results of BSFC for reference engine, 50%-downsized diesel- and 50% downsized biodiesel-fueled engine at different rpm are summarized in Table 5.

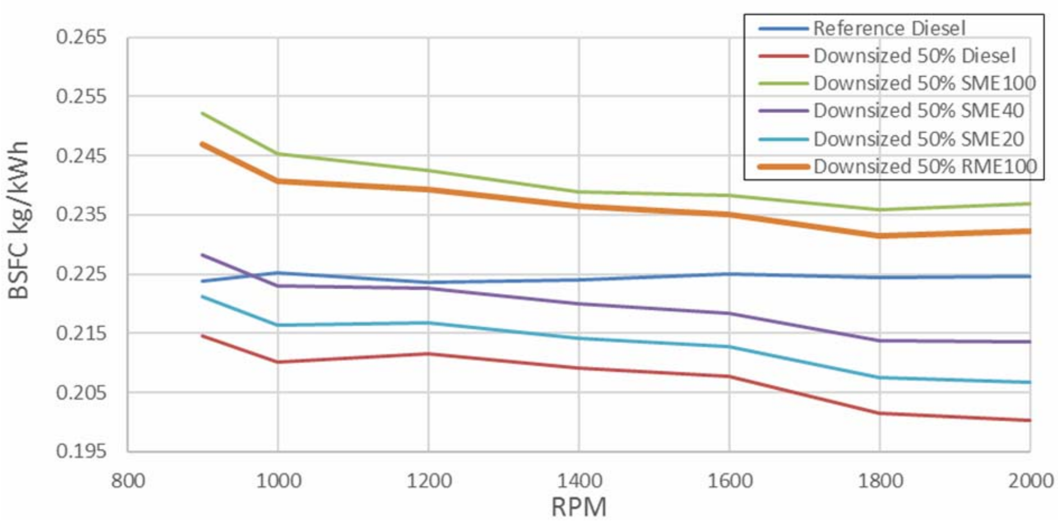


Figure 3. Results of break specific fuel consumption.

Table 5. Summary table of BSFC.

	Brake Specific Fuel Consumption (kg/kWh)					
RPM	Reference Diesel	Downsized 50% Diesel	Downsized 50% SME20	Downsized 50% SME40	Downsized 50% SME100	Downsized 50% RME100
900	0.2238	0.2145	0.2211	0.2282	0.2523	0.2469
1000	0.2253	0.2102	0.2163	0.2230	0.2454	0.2408
1200	0.2236	0.2115	0.2168	0.2225	0.2426	0.2392
1400	0.2240	0.2090	0.2141	0.2199	0.2389	0.2364
1600	0.2251	0.2076	0.2128	0.2185	0.2383	0.2351
1800	0.2244	0.2015	0.2074	0.2138	0.2359	0.2315
2000	0.2246	0.2003	0.2066	0.2135	0.2369	0.2323

Figure 4 shows that for the 50%-downsized engine fueled with biodiesel blends of SME20, SME40, SME100 and RME100, the CO_2 increases 0-1%, 0-4%, 1-6% and 1-4% respectively in the range of 900-2000 rpm compared to that of 50%-downsized engine fueled with diesel. Earlier Richard [15] showed that engine downsizing would benefit the engine in reducing the fuel consumption and CO_2 emission. Agostoa et al. [16] reported that the CO_2 emission level from the engine fueled with biodiesel is higher compared to the engine fueled by diesel due to the oxygen presence in biodiesel molecule which could lead to a nearly complete combustion. The results of CO_2 emission for the reference, 50%-downsized engine fueled with diesel and biodiesel fuels at different rpm are summarized in Table 6.

The average in-cylinder temperature was obtained at 1500 rpm, the regime of maximum engine torque. Figure 5 shows that the average in-cylinder temperature for the reference engine is 2130 K, and the average in-cylinder temperature for the 50%- downsized engine fueled with diesel has increased to 2176 K. Ahmad et al. [17] showed that in-cylinder liner nowadays is capable to withstand the combustion temperature up to 2273 K. This shows that even after the engine is downsized the cylinder liner is still capable of withstanding the extreme temperatures. For the 50%-downsized engine fueled with biodiesel, the average in-cylinder temperature is lower than that fueled with diesel due to lower calorific value of biodiesel blends.

As shown in Figure 6, the NOx emission level increases significantly after the engine has been downsized. The highest NOx emission level occurs at 2000 rpm due to the expected maximum in-cylinder temperature. For the 50%-downsized engine fueled with biodiesel blend of SME20, SME40, SME100 and RME100, the NOx emission level also increases significantly compared to that for the 50%-downsized engine fueled with diesel.

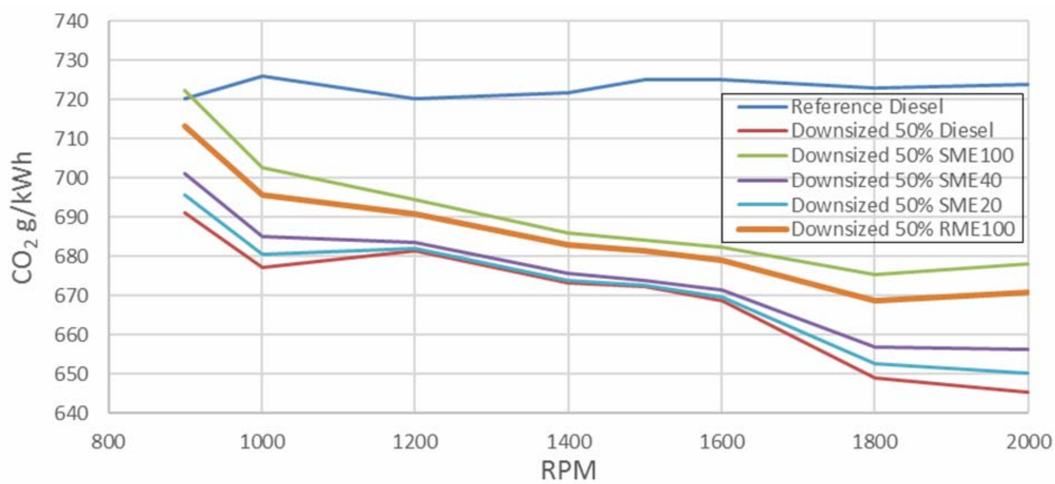


Figure 4. Results of CO_2 emission.

Table 6. Summary table of CO_2 emission.

Specific Carbon Dioxide Emission CO_2 (g/kWh)						
RPM	Manufacturer Diesel	Downsized 50% Diesel	Downsized 50% SME20	Downsized 50% SME40	Downsized 50% SME100	Downsized 50% RME100
900	720.23	691.27	695.75	701.11	722.28	713.21
1000	726.09	677.37	680.67	685.18	702.68	695.63
1200	720.43	681.50	682.24	683.73	694.55	690.98
1400	721.75	673.45	673.83	675.82	685.98	682.99
1500	725.09	672.35	672.78	673.94	684.10	681.47
1600	725.03	668.78	669.62	671.35	682.38	679.21
1800	723.16	649.15	652.72	656.90	675.35	668.87
2000	723.89	645.33	650.19	656.20	678.17	671.00

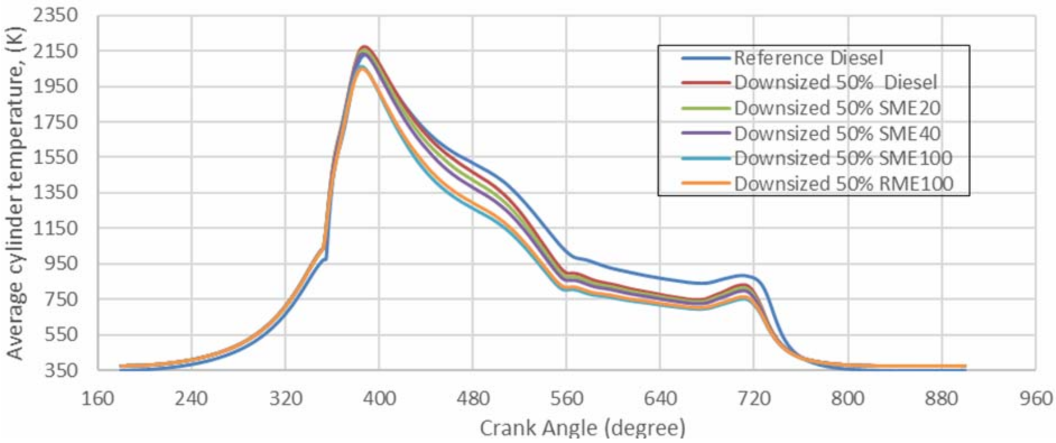


Figure 5. Variation of average cylinder temperature with crank angle at 1500 rpm.

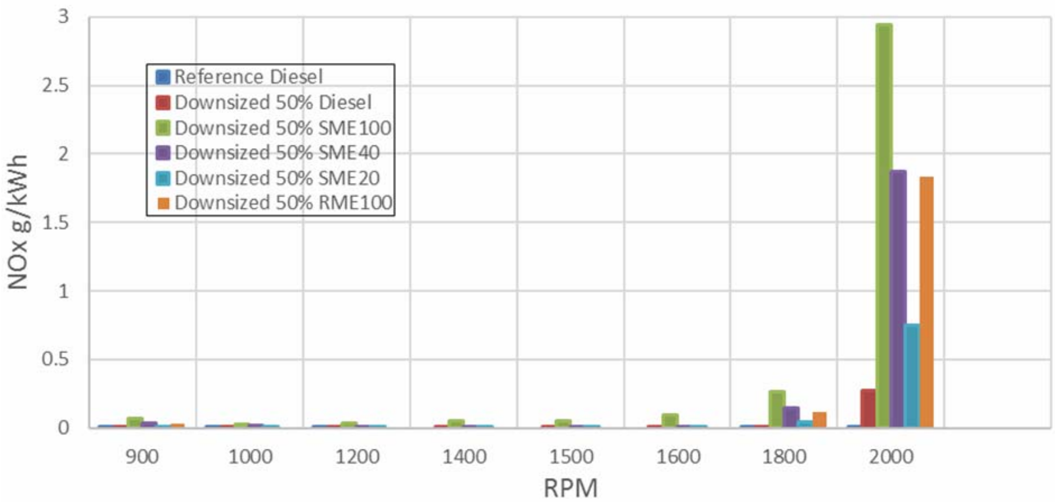


Figure 6. Results of NOx emission.

In order to reduce NOx emission level, the exhaust gas recirculation (EGR) has been applied to the engine [18]. Amir et al. [19] showed that NOx emission rose significantly when higher boost pressure was applied to the engine. NOx emission increases due to a higher boosted pressure which causes higher in-cylinder temperature. Therefore, it does not seem wise and dependable for an engineer to maintain a balanced and normalized perspective on the two conspicuous factors of power and emission. With the high concern to reduce NOx emissions, exhaust gas after-treatment solutions such as, lean NOx traps and selective catalytic reduction (SCR) can be considered to apply to the exhaust system. Engine operation regime at higher rpm, where the NOx formation is expected to be high, can be avoided by engine downspeeding strategy. Moreover, for the type of engine investigated in this work, the engine operation regimes are quite steady and narrow and downsized engine operation with the use of biodiesel blends can be achieved at lower rpm addressing both criteria of fuel consumption and CO_2 reduction and at the same time benefiting from the use of biodiesel fuel with significantly reduced particulate matter (PM) emission level.

As shown in Figure 7, after the engine had been 50%-downsized, the PM emission decreased about 100% compared to that for the reference engine. Due to a very low level of PM emission for SME20, SME40, SME100 and RME100, the results shown in Figure 7 were multiplied for SME20 by 10 and for SME40, SME100 and RME100 by 100. For the downsized engine with application of biodiesel blends of SME20, SME40, SME100 and RME100, the PM emission level significantly decreases compared to that of the 50%- downsized engine fueled with diesel.

Researchers [20, 21] also showed that when biodiesel fuel is used in the engine, the PM emission decreases significantly compared to the diesel fuel due to the several factors such as particle size distribution and the engine working condition. Other researchers [22-24] showed that the influencing factors on the PM concentration of biodiesel engine are very complex due to the fact that PM is usually initiated by the local fuel rich mixture and incomplete combustion. Table 7 shows the reference engine and 50%-downsized diesel fueled engine PM emission comparison to the EU nonroad diesel engine emission standards. The results show that the reference engine complies with the EU Stage II emission standard and the 50%-downsized diesel fueled engine complies with the EU Stage IV emission standard [25].

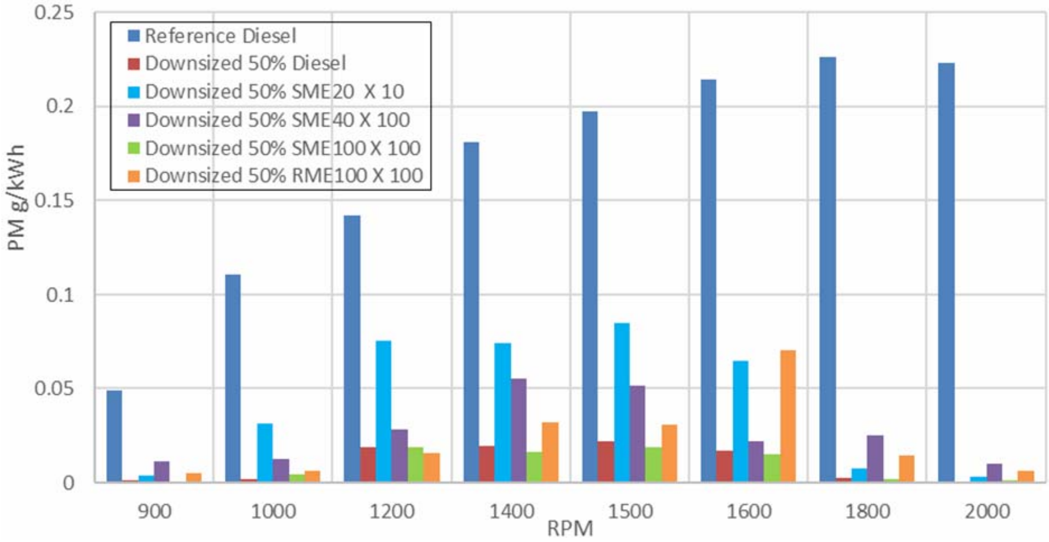


Figure 7. Results of PM emission.

Table 7. PM emission for reference engine and 50% downsized engine.

Particulate Matter (PM) g/kWh			
Reference	50% Downsized	EU Stage II [25]	EU Stage IV [25]
0.22635	0.0224	0.2	0.025

Figure 8 shows the variation of in-cylinder pressure with the cylinder volume for the reference engine fueled with diesel, optimized 50%-downsized engine fueled with diesel, and 50%-downsized engine fueled with biodiesel blends of SME20, SME40, SME100 and RME100. The results show that the in-cylinder pressure of the 50%-downsized engine fueled with diesel increased almost twice compared to that of the reference engine due to the boosted pressure. For the 50%-downsized engine fueled with RME100 the pressure level was the lowest compared to that for SME biodiesel blends.

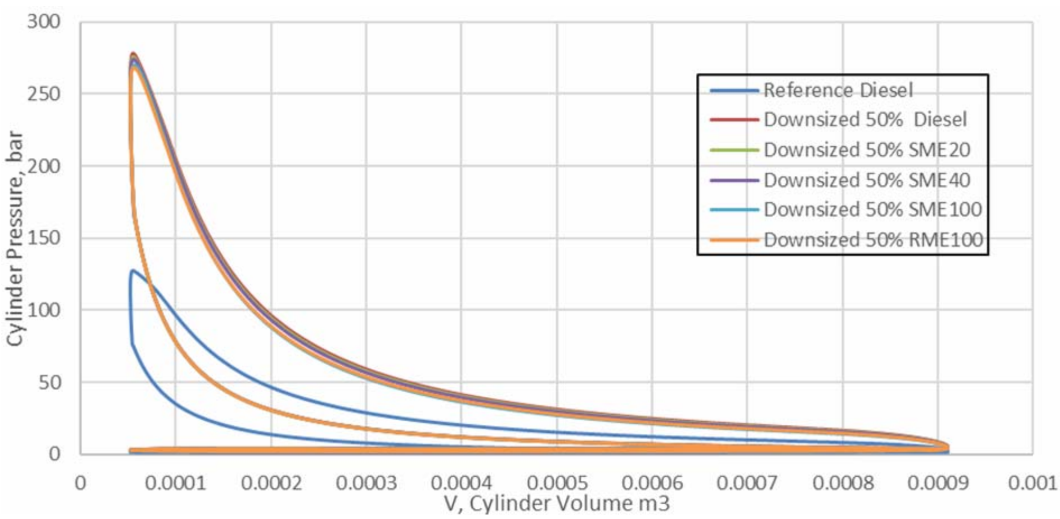
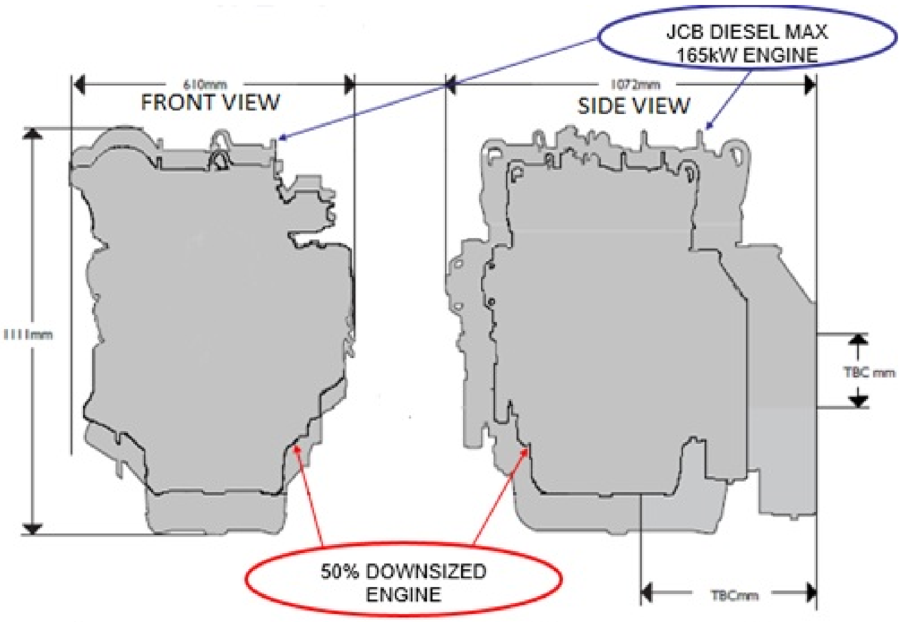


Figure 8. Indicator diagram.

5. Optimized engine design parameters

Figure 9 shows the differences in the engine specifications for the reference or the commercial JCB Diesel Max engine and the 50%-downsized engine. The number of cylinders of the downsized engine has been reduced from 6 to 4 and the bore and stroke length has also been reduced. The engine displacement has been changed from 7.2L to 3.5L and the compression ratio has been increased from 16.9:1 to 17.5:1. The maximum engine power for the 50%- downsized engine was maintained at the same level as the reference engine at 165 kW and the engine torque was at nearly the same level as the reference engine. The boost pressure required for the 50%-downsized engine increased from 1.6 bar to 3.8 bar. The modern turbocharger types available in the market are capable of supplying the boost pressure level required for level of downsizing proposed in this study [26]. Regulated 2-stage and/or advanced 3-stage turbochargers can be used to ensure the highly-boosted engine intake conditions. The high specific power output will be achieved through the use of a larger turbocharger which will inevitably have a detrimental effect upon the low speed torque and transient response of the engine. For example, an electrically powered supercharger (eSupercharger) can be used to enable the transient response and low speed torque to be recovered, resulting in a very high specific output and specific torque characteristic with excellent transient response for good drivability, allowing the downsizing effect to be maximized for minimized CO_2. The unit is capable of running continuously at high boost pressures and high mass flow rates. The capability to operate at full boost continuously sets the eSupercharger apart from so called eBoost systems [27], which only offer short duration boost assist for improvements in engine transient response. Due to its impressively fast response time, the electric supercharger effectively addresses the low speed turbo lag issues associated with downsized engines. Electric superchargers can provide the engine with high boost pressure at low flow rates, equating to both dramatically improved engine performance (with reduced CO_2 emissions) and response at low engine speed.



Engine Model	JCB Diesel Max TCAE-165kW	50% Downsized
Engine Type	Diesel DI, 4-Stroke	Diesel DI, 4-Stroke
No. of Cylinder	6	4
Bore	106	103
Stroke	135	103
Cylinder Capacity	7.2L	3.5L
Compression Ratio	16.9 : 1	17.5 : 1
Maximum Power	165kW	165kW
Maximum Torque	1000Nm @1500RPM	1002Nm @ 1500RPM
Boost Pressure	1.6bar (absolute)	3.8bar (absolute)
Intake Valve Opening	10 (deg. before TDC)	10 (deg. before TDC)
Intake Valve Closing	42 (deg. before TDC)	42 (deg. before TDC)

Figure 9. Comparison of engine parameters for reference and 50% downsized engine.

Table 8 shows the summary of improvements for the 50%-downsized engine compared to the reference JCB Diesel Max engine. The fuel consumption and CO_2 emission decreased in a range of around 4-11 % at 900-2000 rpm range. The PM emissions decreased nearly to 100 % in a range of 900-2000 rpm. However, the opposite trend was observed for NOx emission level, which was significantly higher than that for the reference engine. To alleviate this, exhaust gas aftertreatment solutions along with engine downspeeding strategies must be applied.

Table 8. Improvements in emission reduction.

Fuel Consumption Improvement (kg/kWh)			
RPM	Manufacturer	50% Downsized with EGR	Reduction(%)
900	0.2238	0.2133	4.68
1000	0.2253	0.2085	7.45
1200	0.2236	0.2087	6.66
1400	0.224	0.2059	8.10
1600	0.2251	0.2044	9.18
1800	0.2244	0.1998	10.95
2000	0.2246	0.1991	11.35

CO2 Emission Improvement (g/kWh)			
RPM	Manufacturer	50% Downsized with EGR	Reduction(%)
900	720.23	687.36	4.56
1000	726.09	671.89	7.46
1200	720.43	672.49	6.65
1400	721.75	663.32	8.10
1500	725.09	661.61	8.75
1600	725.03	658.71	9.15
1800	723.16	643.9	10.96
2000	723.89	641.55	11.37

Changes in NOx Emission (g/kWh)			
RPM	Manufacturer	Downsized 50% with EGR	Increment(%)
900	0.000979	0.00154	36.43
1000	0.00000305	0.0006589	99.54
1200	0.000000784	0.000009088	91.37
1400	0.000000577	0.000017667	96.73
1500	0.000000491	0.000016454	97.02
1600	0.000000588	0.000040703	98.56
1800	0.0000077	0.012	99.94
2000	0.00105	0.26953	99.61

Particulate Matter Emission Improvement (g/kWh)			
RPM	Manufacturer	50% Downsized with EGR	Reduction (%)
900	0.04899	0.00119	97.57
1000	0.11056	0.00169	98.47
1200	0.14234	0.01896	86.68
1400	0.18132	0.01964	89.17
1500	0.19742	0.02233	88.69
1600	0.21461	0.01711	92.03
1800	0.22635	0.00224	99.01
2000	0.22308	0.00087662	99.61

6. Conclusion

Engine downsizing technology can help in reducing engine production cost and increase the engine efficiency. This study shows that for the JCB Diesel Max 165kW engine, the maximum of 50% downsizing level can be achieved. Downsizing beyond 50% will not allow delivering 165 kW of break power and 1000 Nm of torque as those of the original JCB engine. Also, the following conclusions are obtained.

1. The results of this study show that it is possible to achieve improved fuel consumption at engine downsizing level of 50 % compared to the reference engine. With the boost pressure of 3.8 bar (absolute), the maximum engine break power and torque can be achieved as 165 kW @ 2000 rpm and 1002 Nm @ 1500 rpm, respectively, with some alterations in compression ratio and engine bore and stroke.
2. 50%-downsized engine fueled with biodiesel produced lower engine break power and torque compared to those of 50%-downsized engine fueled with diesel. Also, 50%-downsized biodiesel fueled engine required higher BSFC compared to 50% downsized diesel fueled.
3. With 50% engine downsizing level CO_2 and PM emission levels significantly decreased and PM emission level was in compliance with the EU stage IV nonroad diesel engine emission standards. However, it also caused the NOx emission level to increase compared to the reference engine. Also, 50%-downsized biodiesel-fueled engine produced higher level of CO_2 and NOx emissions but lower level of PM emissions compared to those of diesel-fueled engine.

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Xian Mian Tan received MSc degree in Mechanical Engineering from the University of Northumbria, UK in 2017. He worked on the project of diesel engine downsizing and optimization with application of various biodiesel fuel blends. He also has knowledge and expertise in mechanical stress analysis, vibration and product design and development, computational thermofluids, and other mechanical engineering related areas.
E-mail address: xianmiantan@hotmail.com

Ulugbek Azimov is a Senior Lecturer in Mechanical Engineering at the University of Northumbria, UK. He received his MSc degree in Mechanical Engineering from Texas A&M University, USA and PhD in Mechanical Engineering from Chonnam National University, South Korea. His research area includes combustion, alternative fuels, clean renewable energy systems and energy conversion and conservation. He is a fellow of Higher Education Academy UK.
E-mail address: ulugbek.azimov@northumbria.ac.uk

