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Cylinder Deactivation for Increased Engine Efficiency and Aftertreatment Thermal Management in Diesel Engines

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Abstract

Diesel engine cylinder deactivation (CDA) can be used to reduce petroleum consumption and greenhouse gas (GHG) emissions of the global freight transportation system. Heavy duty trucks require complex exhaust aftertreatment (A/T) in order to meet stringent emission regulations. Efficient reduction of engine-out emissions require a certain A/T system temperature range, which is achieved by thermal management via control of engine exhaust flow and temperature. Fuel efficient thermal management is a significant challenge, particularly during cold start, extended idle, urban driving, and vehicle operation in cold ambient conditions. CDA results in airflow reductions at low loads. Airflow reductions generally result in higher exhaust gas temperatures and lower exhaust flow rates, which are beneficial for maintaining already elevated component temperatures. Airflow reductions also reduce pumping work, which improves fuel efficiency. The fuel economy and thermal management benefits of one-third engine CDA, half-engine CDA and two-third engine CDA have been studied at key operating conditions. CDA improves the fuel efficiency at steady state loaded idle operation by 40% with similar engine out temperatures and lower exhaust flow rates compared to conventional thermal management strategies as demonstrated with an inline six (I6) cylinder medium duty diesel engine used in this study. The lower exhaust flow rates due to CDA help maintain elevated A/T temperatures via reduced heat transfer losses. At elevated engine speeds, CDA provides a 5% - 32% BTE improvement in fuel economy, increased rate of A/T warm-up, higher temperatures steady state temperatures, and allow for active diesel particulate filter regeneration without hydrocarbon dosing of the diesel oxidation catalyst. During highway cruise, half-engine CDA and two-third engine CDA can be used to reach engine outlet temperatures of 520 to 570° C, a 170 to 220° C increase compared to normal operation. Full engine CDA enables 78% reduction in motoring torque at an engine speed of 2100 rpm and thus could help save fuel and keep the A/T warm during vehicle coast.

Introduction

Fuel consumption for heavy duty trucks is expected to double in United States of America by 2050[1]. Strict emission regulations by United States Environmental Protection Agency (EPA) to improve air quality and the increasing demand for heavy duty transportation drive innovation of advanced engines and auxiliary systems. One such system is the aftertreatment system which converts the exhaust pollutants such as NOx, unburnt HCs and particulate matter (PM) from the diesel engine into harmless products. The effectiveness of most of these systems is limited when exhaust temperatures are low (usually below 250C) as the conversion efficiency is low at those temperatures. Current tailpipe limits for heavy-duty on-highway diesel engines in the United States are 0.2 g/bhp-hr for NOx, 0.01 g/bhp-hr for PM, and 0.14 g/bhp-hr for uHC[2]. Thermal management strategies designed to increase aftertreatment component temperatures are needed for efficient aftertreatment operation over a wide range of engine operating conditions[3;4]. Specifically, aftertreatment thermal management includes temperature increase (stay-warm), and maintenance (stay-warm), of the aftertreatment system components via control of engine exhaust flow and turbine outlet temperature (TOT). Advanced valvetrain strategies such as cylinder deactivation (CDA) allow for fuel efficient thermal management.

Research on methods to improve aftertreatment thermal management by means of increased diesel engine exhaust temperatures[5;6] by using advanced valvetrain technologies such as variable valve actuation (VVA)7, 8, 9, 10, 11, 12, 13 is underway. VVA technologies include technologies such as

CDA, intake valve closure modulation and alternate breathing strategies such as rebreathing and reverse breathing[14]. These variable valve actuation strategies such as CDA essentially have a reduction in airflow which reduces the air-to-fuel ratio (AFR) thereby increasing TOT[10;13]. Hence these strategies can be employed to increase the exhaust temperatures thereby aiding in thermal management.

The impact of advanced valve-train strategies on aftertreatment thermal management can be assessed by evaluating strategies during operation in standardized test procedures, including the heavy duty federal test procedure (HD-FTP). The engine operates at the loaded idle operation for about 40% of the time during the HD-FTP. TOTs and exhaust flow rates during this condition therefore have a significant impact on the ability of the engine to warm-up, maintain, or cool the A/T components.

Figure 1 maps the HD-FTP cycle to 8 steady state operating conditions and the number displayed next to each bubble signifies the percentage of fuel consumed at these speeds and brake mean effective pressures (BMEP). As shown, approximately 5.8% of the fuel is consumed near the loaded idle (800 RPM/ 1.3 bar BMEP) operating condition. About 9% fuel is consumed at high speed low load (2200 RPM/ 1.3-5.1 bar BMEP) operating conditions. Fuel efficient thermal management is a challenge at these operating conditions if conventional methods are used.

The TOT is low and exhaust flow is high at loaded Idle and high speed low load operating conditions, thus leading to an inefficient aftertreatment thermal performance. Figure 2 shows TOT contours in the engine speed load space for a modern diesel engine[15]. The figure shows that the temperatures are too cold at low load (< 3-4 bar BMEP) operating conditions. Hence there is a need to improve TOT in this operating load range in an efficient manner.

CDA, wherein fuel and valves are deactivated, for a certain number of cylinders enables efficient aftreatement thermal management. Through deactivation the airflow is reduced which enables higher TOT via decreased AFRs at low loads to improve thermal performance of the aftertreatment. Previous research has demonstrated that cylinder deactivation (CDA) is a fuel efficient method for maintaining elevated A/T component temperatures during idle operation[11;13], and for enabling active DPF regeneration without requiring DOC fuel dosing during highway cruise conditions[9;12]. Joshi et al.[13] implemented half engine CDA (3-cylinder) during idle over the HD-FTP to achieve a 3.4% fuel savings without sacrificing A/T performance. This paper summarizes CDA benefits for a Cummins inline, six cylinder, medium duty diesel engine at low loads, cruise and motoring operation. This paper also includes novel results at loaded idle for one-third engine (2-cylinder) CDA strategy. Full engine CDA benefits at motoring conditions over various engine speed is also discussed in this paper as on road trucks spend a lot of time in motoring conditions.

FIGURE 1 Fuel consumption distribution over a HD-FTP mapped to 8 steady state operating conditions. The cross hatched red bubble represents loaded idle operation and the dotted red bubble represents high speed low load operation.

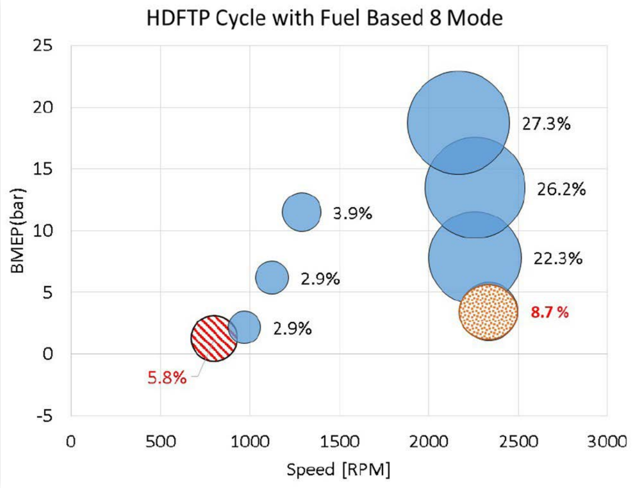

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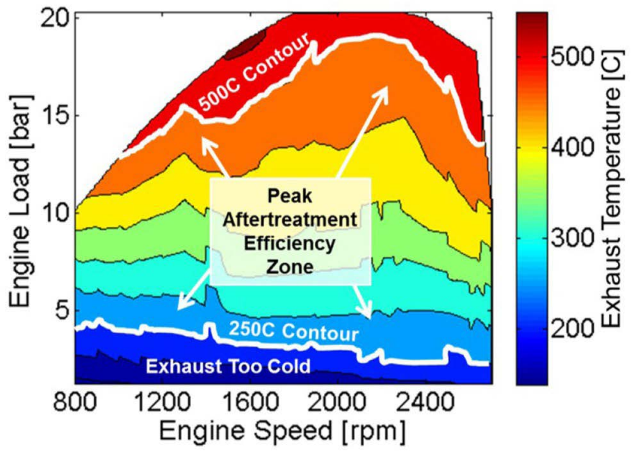
FIGURE 2 Exhaust Temperatures as a function of engine speed and engine load for a modern diesel engine. The peak aftertreatment efficiency zone is marked in the region where the temperature is between 250-500° C. The temperatures is too cold at low load operating conditions.



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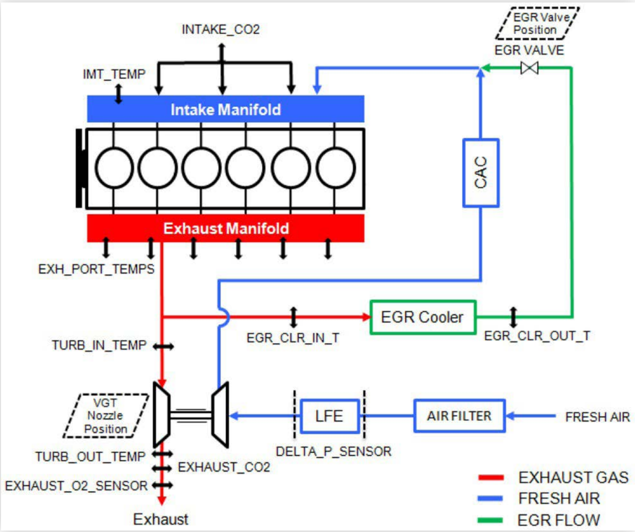
Experimental Setup

The experimental testbed used in this study is a camless six-cylinder Cummins diesel engine outfitted with an electro-hydraulic VVA system, high-pressure cooled EGR, a sliding nozzle-type variable geometry turbine (VGT) turbocharger, an air-to-water charge air cooler, and a common rail fuel injection system. The engine is connected to a Power Test AC dynamometer via a flexible drive shaft, which controls the speed and applies load to the engine. A schematic of the system is presented in Figure 3.

The fresh intake air flows through a laminar flow element into the compressor and is then cooled via a charge air cooler. The exhaust from the cylinders flows either into the EGR system or through the turbine of the VGT to the exhaust pipe.

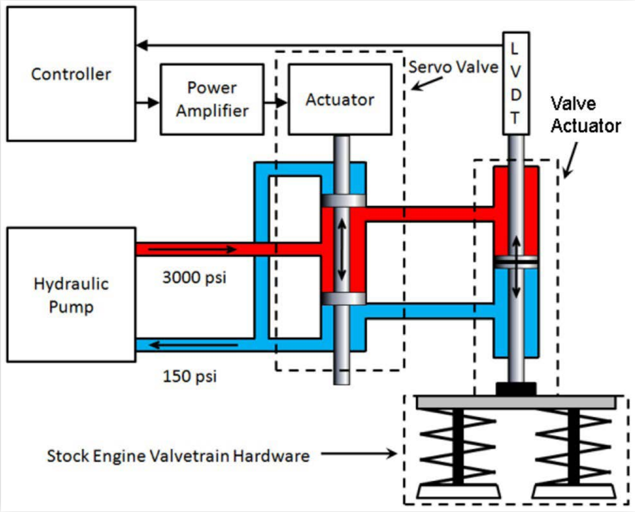
FIGURE 3 Schematic of the camless Cummins multicylinder engine testbed used for this study.



The exhaust temperature is measured at the outlet of the turbine and is referred to in this paper as TOT. Two Kistler 6067 and four AVL QC34C in-cylinder pressure transducers are used in tandem with an AVL 365C crankshaft position encoder and an AVL 621 Indicom module for high-speed in-cylinder pressure data acquisition. Laboratory-grade fuel flow measurement is used to measure the fuel consumption.

Both the intake and exhaust valve pairs for each of the 6 cylinders are actuated by the VVA system. The actuators use position feedback for closed-loop control, enabling cylinder independent, cycle-to-cycle control of the valve actuation. Figure 4 presents a schematic of the VVA system used at Purdue University. The valve profiles are generated in Simulink and the dSPACE hardware is used to transmit voltage feedback to the servo valves via the controllers and amplifiers. These actuators push on the valve pairs through a valve bridge to open them. The return force from the valve springs close the valves as the actuators retract.

FIGURE 4 Schematic of Purdue variable valve actuation (VVA) system.



A dSPACE interface is used to control the VVA system, send and receive data from the ECM, and samples all the external measurement channels. The motoring experiments were carried out at Eaton using another VVA system with a similar medium duty diesel engine.

Methodology

This study includes four key steady state operating conditions to evaluate CDA. The experiments were performed to study the fuel economy and A/T thermal management benefits of CDA at the following operating conditions:

1. Loaded Idle operation (800 RPM, 1.3 bar BMEP)
2. High speed operation (2200 RPM, 1.3-5.1 bar BMEP)
3. Cruise operation (1200 RPM, 7.6 bar BMEP)
4. Motoring operation

All experimental data shown and discussed in the following sections are subjected to strict mechanical constraints shown in Table 1. These constraints were taken into consideration to have safe engine operation and not damage the experimental setup. The VGT position, EGR valve position and fuel injection timing for CDA was optimized via detailed screening for maximum fuel efficiency. The emission levels of conventional 6-cylinder operation are set as constraints for the CDA strategies. Further optimization would enable to realize more benefits for CDA. Engine-cycle efficiency analysis is carried out in order to understand the fuel efficiency benefits. The brake thermal efficiency (BTE) of the engine is the product of the closed cycle efficiency (CCE), open cycle efficiency (OCE), and mechanical efficiency (as shown in Equation 1). CCE is affected by combustion completeness, piston expansion work, and in-cylinder heat transfer. OCE quantifies the effectiveness of the gas exchange and is affected by the pressure difference between the intake and exhaust manifolds and cylinder valve timings. The mechanical efficiency captures losses from friction, parasitic loads and heat losses in motoring cylinders. The power to drive the hydraulic VVA pump is not included in the mechanical loss calculation. Additional information of the cycle efficiency analysis can be found in[1].

$$\text{BTE} = \eta_{\text{close cycle}} \times \eta_{\text{open cycle}} \times \eta_{\text{mechanical}} \tag{1}$$

TABLE 1 Mechanical constraints.

Mechanical Parameter	Unit	Limit
Turbine Inlet Temperature	˚C	760
Compressor Outlet Temperature	˚C	230
Turbo Speed	kRPM	126
Peak Cylinder Pressure	bar	172
Exhaust Manifold Pressure	kPa	500
In-cylinder Pressure Rise Rate	bar/ms	100

Strategy Description

This section outlines the different CDA strategies compared with 6-cylinder operation for effective A/T stay-warm operation at different operating conditions. CDA is achieved by deactivating valve motion and fuel for a certain number of cylinders.

6-cylinder Figure 5 illustrates the gas exchange during conventional 6-cylinder operation. The strategy defined as "6-cylinder best BSFC (Brake Specific Fuel Consumption)" is conventional 6-cylinder operation tuned for minimum fuel consumption and is used as a fuel consumption baseline for all the operating conditions. The 6-cylinder thermal management strategy defined as "6-cylinder warm up" and is implemented via a maximally closed VGT nozzle position and four late injections (which result in a fuel-inefficient delayed heat release) to increase TOT and exhaust flow rate for accelerated A/T warm-up, albeit at the expense of increased fuel consumption. This strategy is used as baseline to compare CDA at loaded idle operation. "6-cylinder delayed SOI" is where the start of injection (SOI) is delayed to delay the heat release rate to increase the TOT, and is strategy as a 6-cylinder baseline for cruise operation.

2-cylinder (one-third engine) operation Figure 6 illustrates the gas exchange during two cylinder operation wherein both valve motion and fuel injection is deactivated for cylinders 1, 2, 5 and 6. There is fuel combustion occurring only in cylinders 3 and 4. This 2-cylinder firing strategy is referred as "2-cylinder" in this study and compared with 6-cylinder baselines at loaded idle operation.

FIGURE 5 Conventional 6-cylinder Operation.

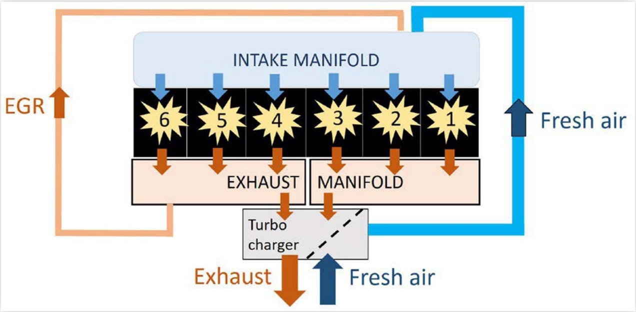


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FIGURE 6 2-cylinder (one-third engine) firing operation showing the gas exchange in engine wherein both valve motion and fuel injection is deactivated for cylinders 1, 2, 5 and 6.

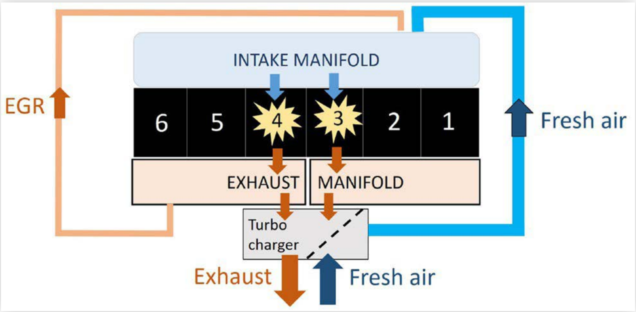

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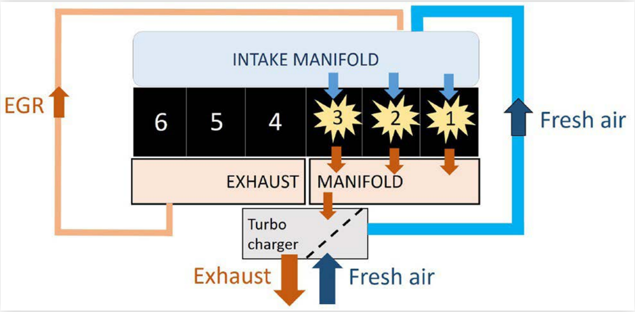
FIGURE 7 3-cylinder (half-engine) firing operation showing the gas exchange in the engine wherein both valve motion and fuel injection is deactivated for cylinders 4, 5 and 6.



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3-cylinder (half engine) operation Figure 7 illustrates the gas exchange during three cylinder operation wherein both valve motion and fuel injection is deactivated for cylinders 4, 5 and 6. There is fuel combustion occurring only in cylinders 1, 2 and 3. This 3-cylinder firing strategy is referred as "3-cylinder" in this study and is compared with 6-cylinder baselines at various operating conditions.

4-cylinder (two-third engine) operation Figure 8 illustrates the gas exchange during three cylinder operation wherein both valve motion and fuel injection is deactivated for cylinders 2 and 5. There is fuel combustion occurring only in cylinders 1, 3, 5 and 6. This 4-cylinder firing strategy is compared with 6-cylinder baselines at cruise and high speed low load operation.

Full engine CDA operation Full engine CDA is achieved by deactivation of valve motion and fuel injection for all the cylinders. Figure 9 illustrates this strategy, wherein valve motion and fuel injection is deactivated for all 6 cylinders. This strategy is compared with 6-cylinder and other CDA strategies during motoring operation.

FIGURE 8 4-cylinder (two-third engine) firing operation showing the gas exchange wherein both valve motion and fuel injection is deactivated for cylinders 2 and 5.

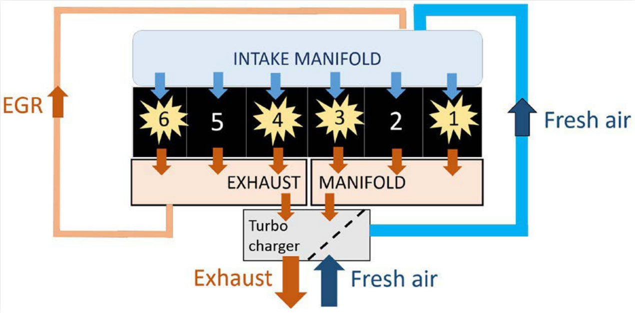

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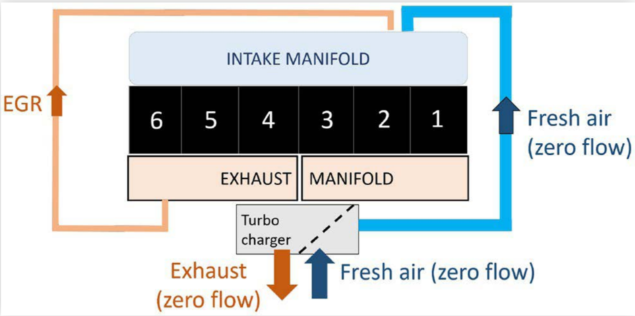
FIGURE 9 Full engine CDA operation showing complete deactivation of both valve motion and fuel injection in all 6 cylinders.



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Experimental Results

This section is divided into the following four subsections each talking about the benefits of CDA at different operating conditions.

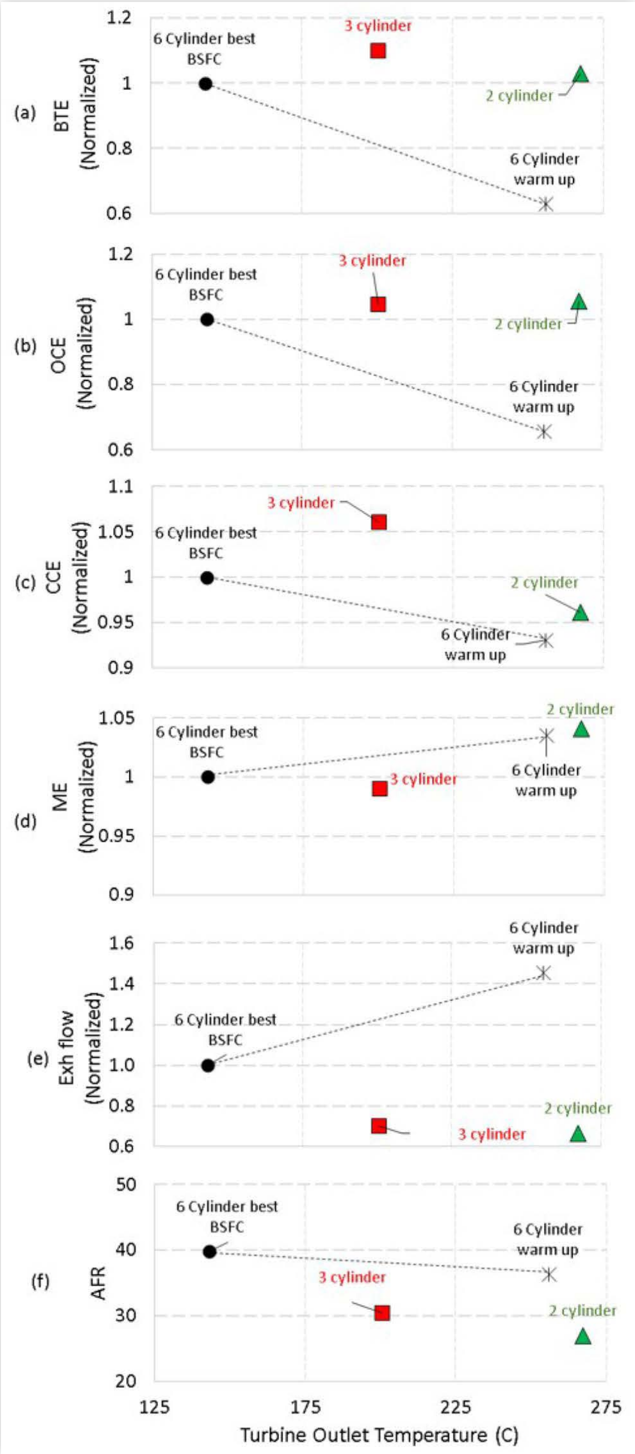
Loaded Idle Operation (800 RPM, 1.3 BAR BMEP)

This section discusses about the fuel efficiency benefits of "2-cylinder" and "3-cylinder" operation compared with conventional "6-cylinder" operation at loaded idle (800 RPM, 1.3 bar BMEP). Figure 10 shows the experimental steady state results at loaded idle (800 RPM, 1.3 bar BMEP) showing normalized (a) BSFC, (b) BTE, (c) OCE, (d) CCE, (e) ME, (f) exhaust flow and (g) AFR vs TOT for all the strategies. The "6-cylinder best BSFC" strategy is the engine tuned to achieve best fuel efficiency whereas the "6-cylinder warm up" is the strategy used for warming up the aftertreatment.

The "3-cylinder" strategy is 10% more fuel efficient with 60°C increase in TOT when compared to the "6-cylinder best BSFC" strategy as shown in Figure 10 (a). The BTE increase is due to the OCE and CCE improvement while in "3-cylinder" mode as shown in Figure 10 (b) and (c). The TOT increase is primarily due to the decrease in AFR (per Figure 10 (f)).

Upon further deactivation of another cylinder, the "2-cylinder" reaches a TOT of 260°C which is an 120°C increase in TOT with 3% increase in BTE as shown in Figure 10 (a) primarily due to OCE improvement. The "2-cylinder" strategy also is able to reach TOTs higher than the "6-cylinder warm up" mode while being 40% more fuel efficient. This means that the "2-cylinder" strategy can keep the aftertreatment in the maximum efficiency temperature zone while saving 40% fuel while operating loaded idle operating condition. Exhaust flow plays a vital role in supplying heat and reducing the heat transferred to the aftertreatment from the engine. When the aftertreatment is at its efficient temperature zone, a lower exhaust flow is preferred to maintain the aftertreatment temperature[13]. "3-cylinder" and "2-cylinder" strategies both have about 80% lower exhaust flow when compared to "6-cylinder warm up" mode and about 30% lower exhaust flow when compared to "6-cylinder best BSFC" strategy. In summary, "3-cylinder" and "2-cylinder" has higher TOT and better BTE than "6-cylinder" engine operation.

FIGURE 10 Experimental steady state results at loaded idle (800 RPM, 1.3 bar BMEP) showing normalized (a) BTE, (b) OCE, (c) CCE, (d) ME, (e) Exhaust flow and (f) AFR vs TOT for all the strategies.



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Approximate steady state heat transfer rate to the A/T components are compared for each strategy in order to evaluate the stay-warm capabilities of each of the strategies. The heat transfer rate between the exhaust gas and an aftertreatment catalyst depends on the TOT, exhaust flow rate, and instantaneous catalyst bed temperature. The heat transfer rate between incoming gas into the A/T and the catalyst bed[11], is given by Equation 2:

$$q = C \times \dot{m}^{4/5} \times \left(TOT - T_{Catalyst} \right) \tag{2}$$

where $\dot{m}$ is the exhaust mass flow rate going through the catalyst, $T_{Catalyst}$ is the temperature of the catalyst, and C is a constant that depends on the material of the catalyst.

The model yields a predicted heat transfer rate from the exhaust gas to the catalyst for each $T_{Catalyst}$, by using the exhaust mass flow rate and the TOT. A positive heat transfer rate corresponds to catalyst warm up as heat is transferred from the exhaust gas to the catalyst. Negative heat transfer rate corresponds to catalyst cooling down as the heat is transferred from the catalyst to the exhaust gas.

The heat transfer rate to the catalyst at different catalyst bed temperatures is compared as shown in Figure 11 to evaluate the stay-warm potential of CDA strategy. The predicted heat transfer rates are normalized using the heat transfer rate of “6-cylinder best BSFC” case at a catalyst bed temperature of 0˚C. The slope of the line is determined by exhaust flow and the TOT determines where the line crosses the x-axis. Lower exhaust flow and a higher TOT is preferred for efficient stay-warm performance. “3-cylinder” and “2-cylinder” strategies have higher heat transfer rates than “6 cylinder best BSFC” strategy at all catalyst bed temperatures. “2-cylinder” strategy is preferred at temperatures above 250˚C due to its lower negative heat transfer rates when compared to “6-cylinder warm up” strategy.

High Speed Operation (2200 RPM, 1.3-5.1 BAR BMEP)

Figure 12 (a) shows the BTE improvements achieved via deactivating the cylinders through the BMEP range at 2200 RPM engine speed. The results are normalized with respect to the “6-cylinder best BSFC” strategy. The results show that BTE improvements between 5 and 32% are possible depending on

FIGURE 11 Catalyst warm up characteristics comparing the heat release rates of 2 and 3 cylinder strategies with conventional 6 cylinder strategies. The heat release rate is also a good proxy for enthalpy of the exhaust gas.

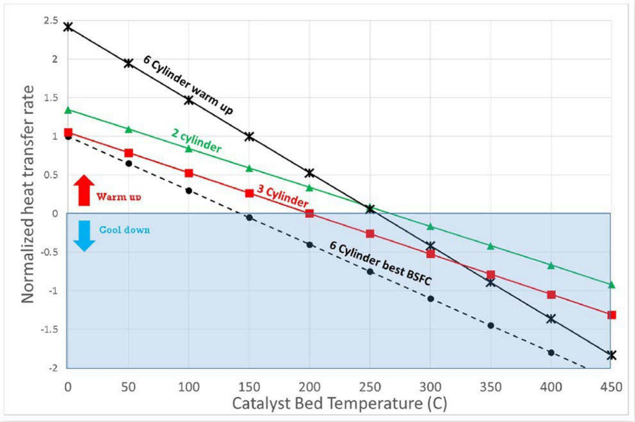

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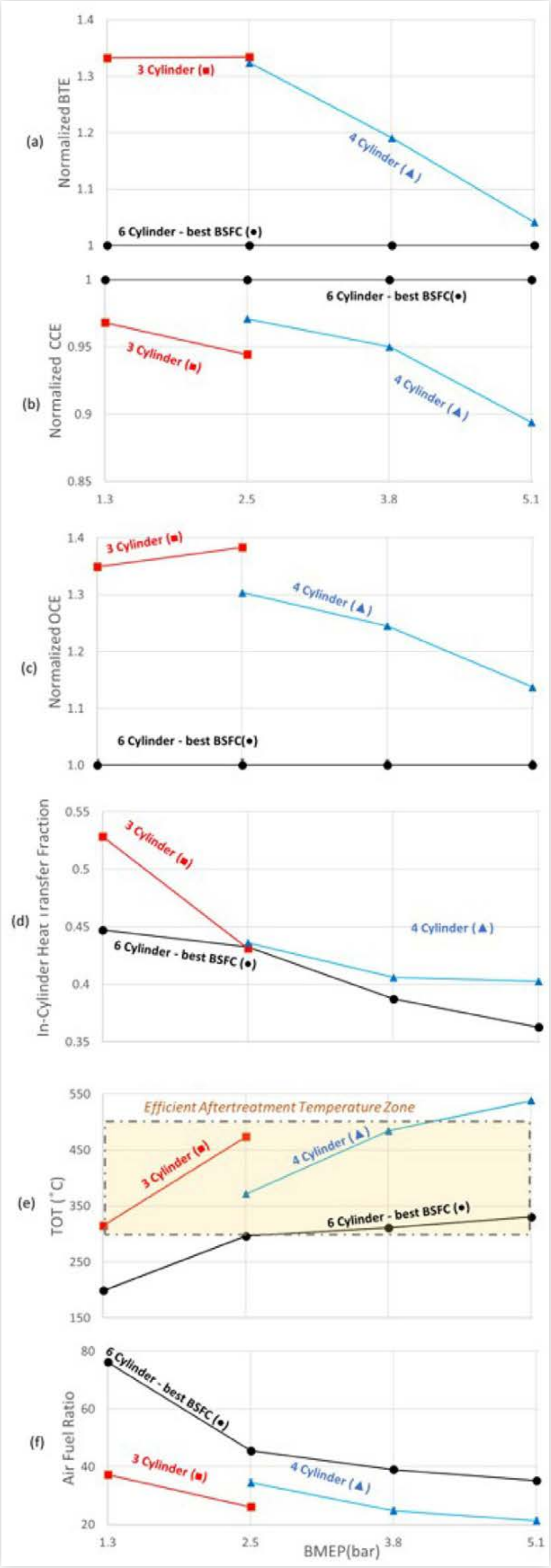
FIGURE 12 Experimental steady state results at loaded idle (2200 RPM, 1.3-5.1 bar BMEP) showing normalized (a) BTE, (b) CCE, (c) OCE, (d) In-cylinder HT fraction (e) TOT, (f) AFR vs BMEP for all the strategies.



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load (e.g., BMEP). This is primarily a result of a 35% increase in the open cycle efficiency, per Figure 12 (c), achieved through a reduction in pumping work. Pumping work is lower because airflow is lower, as shown in Figure 12 (f). Airflow is lower as a result of a reduction in displaced volume via deactivation of cylinders. The fuel efficiency benefit relative to the stock calibration decreases as the load increases due to relative reductions in the OCE benefits. The CCE is decreased for "3-cylinder" and "4-cylinder" strategies due to the higher incylinder heat losses due to higher per cylinder fuel injection as shown in Figure 12 (b) and (d).

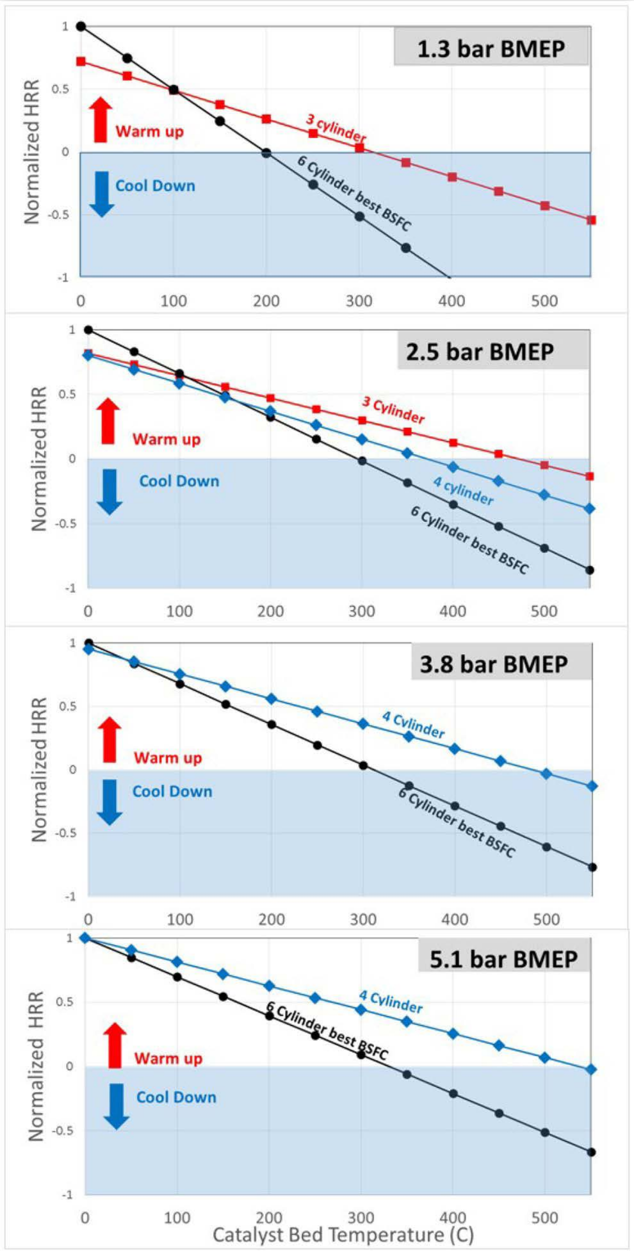
During low load operation the TOT is not warm enough for"6-cylinder best BSFC" operation to maintain the aftertreatment at effective operating range as shown in Figure 12 (e). Reducing the air-to-fuel ratio (AFR) is the most direct way to increase TOT. The most fuel efficient way to reduce AFR is by reducing the airflow (as opposed to increasing the fuel injected) via CDA as shown in Figure 12 (f). "3-cylinder" and "4-cylinder" strategies enable to reach the effective aftertreatment temperatures at all the low loads till 5.1 bar BMEP.

During cold start conditions the aftertreatment system would ideally warm-up as quickly as possible. Approximate steady state heat transfer rate to the A/T components (per Equation 2) are compared for each strategy in Figure 13 in order to evaluate the aftertreatment stay-warm and warm up capabilities of each of the strategies. The predicted heat transfer rates are normalized by the "6 cylinder best BSFC" case at a catalyst bed temperature of 0°C for each load. The result allows assessment of the relative warm-up characteristic of each strategy, at various loads from 1.3 to 5.1 bar BMEP. A higher heat transfer rate is preferred during the catalyst warm-up phase and is achieved using the optimal combination of exhaust flow and TOT for a particular catalyst bed temperature.

"6-cylinder best BSFC" has highest heat transfer rate when the catalyst bed temperature is lower than 100°C due to higher exhaust flow at 1.3 bar BMEP. The "3-cylinder" mode outperforms "6-cylinder best BSFC" above catalyst bed temperatures of 100°C, as the higher TOTs enables higher heat transfer rates from exhaust gas to catalyst bed. The catalyst can only reach a temperature of 200°C if the engine only operates in the "6-cylinder best BSFC", whereas 3-cylinder mode enables catalyst temperatures up to 300°C.

"6-cylinder best BSFC" mode will result in the highest gas-to-bed heat transfer rates when the bed temperature is below 100°C at 2.5 bar BMEP, while the "3-cylinder" mode is preferred above this temperature. The "3-cylinder" strategy can heat the catalyst to temperatures in excess of 470°C. The "4-cylinder" yields a higher heat transfer at all catalyst bed temperatures due to increased TOT, at 3.8 and 5.1 bar BMEP operation.

FIGURE 13 Catalyst warm up characteristics comparing 3 and 4 cylinder strategies with 6 cylinder strategies for 2200 RPM/1.3-5.1 bar BMEP. The heat release rates at each load are normalized w.r.t heat release rate of 6 cylinder best BSFC strategy at 0°C. A positive heat transfer rate indicates catalyst warm up and a negative heat transfer rate indicates catalyst cool down. The heat release rate is also a good proxy for enthalpy of the exhaust gas.



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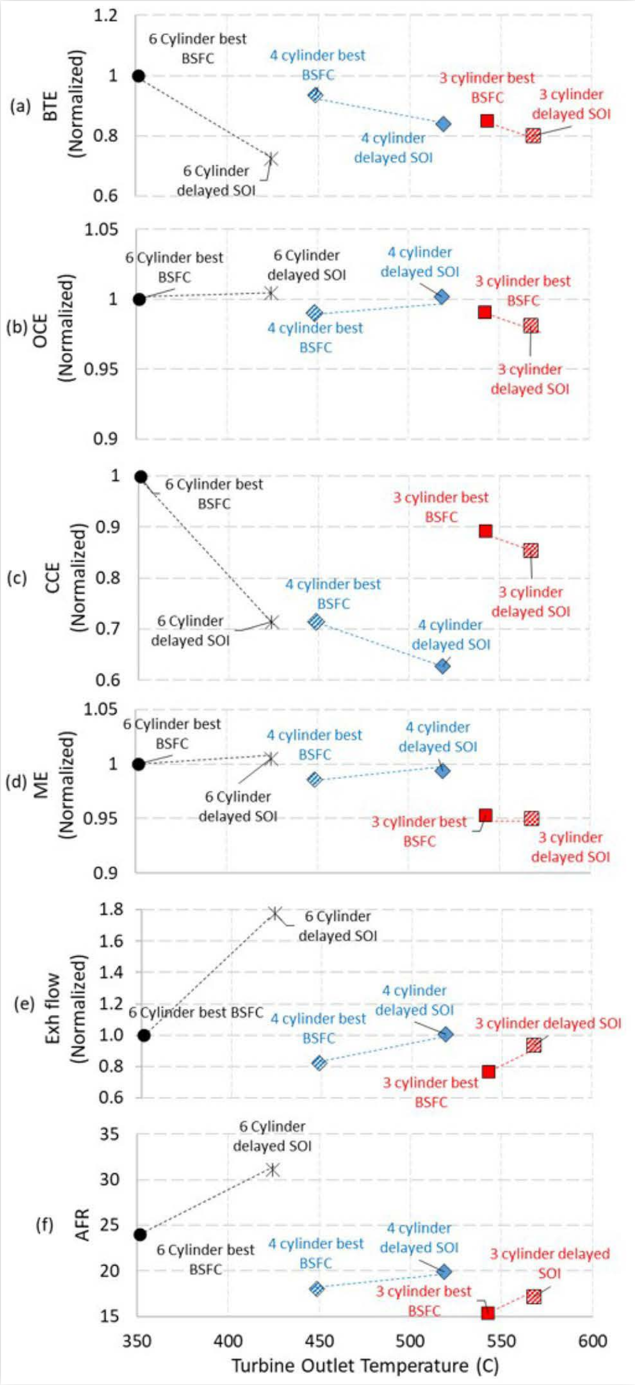
Cruise Operation (1200 RPM, 7.6 BAR BMEP)

CDA is not a preferred strategy at loads higher than 5.1 bar BMEP as the efficiency drops as load is increased. However CDA strategies are analyzed at this operating load to understand the thermal management benefits including active regeneration potential of CDA at this load. Figure 14 shows the experimental steady state results at cruise (1200 RPM, 7.6 bar BMEP) operation showing normalized (a) BTE, (b) CCE, (c) OCE, (d) ME (e) Exhaust Flow, (f) AFR vs TOT for all the strategies. "3-cylinder" and "4-cylinder" strategies are compared with "6-cylinder" strategy. The best BSFC strategy optimizes for fuel efficiency and the delayed SOI strategy aims to maximize the TOT.

Figure 14(a) shows that the highest BTE is achieved when all six cylinders are activated. This is in contrast to improved

FIGURE 14 Experimental steady state results at cruise (1200 RPM, 7.6 bar BMEP) showing normalized (a) BTE, (b) CCE, (c) OCE, (d) ME (e) Exhaust Flow, (f) AFR vs TOT for all the strategies.



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efficiencies with cylinder deactivation at lower loads as seen in previous sections. The "3-cylinder" and "4-cylinder" strategies have 7-18% lower BTE when compared to the "6-cylinder best BSFC" strategy due to lower CCE as shown in Figure 14(c). The CCE is decreased for the best BSFC CDA cases because of increased per cylinder fueling in the active cylinders leading to a higher heat loss to the cylinder walls. There is no improvement in OCE for CDA as shown in Figure 14(b) at the cruise operation as the 6-cylinder OCE is already close to 100% as the engine is tuned to operate at maximum efficiency at this condition. However when the goal is to increase TOT in a fuel efficient manner, "3-cylinder delayed SOI" and "4-cylinder delayed SOI" strategies outperform "6-cylinder delayed SOI" strategy. Figure 14(a) demonstrates that TOT in excess of 550˚C are possible with "3-cylinder delayed SOI" and 520˚C for "4-cylinder dealyed SOI", where as the maximum possible temperature during "6-cylinder delayed SOI" operation does not exceed 420˚C. The higher TOT is achieved via lowering of AFR as shown in Figure 14(f). CDA enables TOT of 520550˚C as seen in Figure 14, which is hot enough to actively regenerate a DPF without fuel-dosing a DOC or burner. In contrast, 420˚C is the highest temperature achieved during 6 cylinder operation even with delayed SOI. Hence CDA also enables fuel savings during active DPF regeneration.

Approximate steady state heat transfer rate to the A/T components (per Equation 2) are compared for each strategy in Figure 15 in order to evaluate the aftertreatment stay-warm and warm up capabilities of each of the strategies at cruise operation. "6-cylinder delayed SOI" has a higher heat transfer rate for catalyst bed temperatures below 200˚C. "3-cylinder delayed SOI" is the preferred strategy at catalyst bed temperatures above 200˚C. "4-cylinder delayed SOI" has higher heat transfer rate than "6-cylinder delayed SOI" for catalyst bed temperatures above 250˚C and warms up the catalyst upto 520˚C. It was also observed that the PM levels was elevated for 3-cylinder operation due to low AFR. Hence "4-cylinder delayed" is preferred strategy at the cruise operating speed and load.

Motoring Operation

Motoring is defined as engine operation where no fuel is injected in the cylinders. Motoring occurs regularly during decelerations or during vehicle coast. Figure 16 below shows

FIGURE 15 Catalyst warm up characteristics comparing 3 and 4 cylinder strategies with 6 cylinder strategies for 1200 RPM/7.6 bar BMEP. The heat release rates at each load are normalized w.r.t heat release rate of "6-cylinder best BSFC" strategy at 0˚C. A positive heat transfer rate indicates catalyst warm up and a negative heat transfer rate indicates catalyst cool down. The heat release rate is also a good proxy for enthalpy of the exhaust gas.

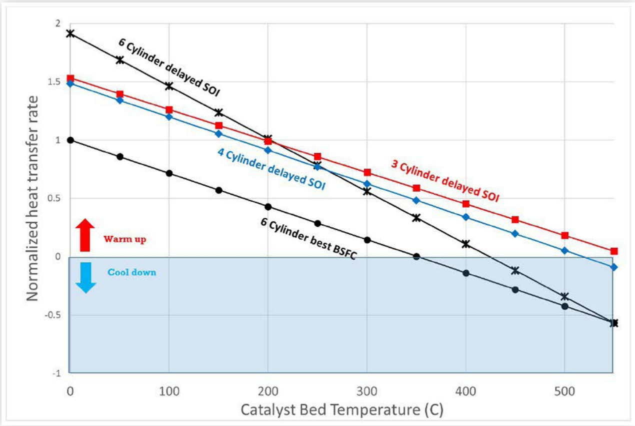

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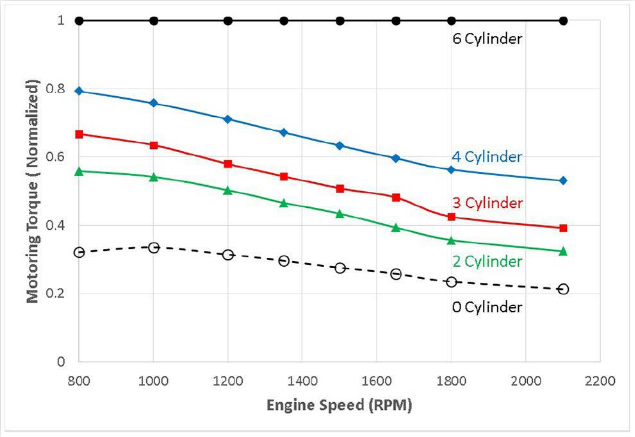
FIGURE 16 Motoring Torque required to run the engine at speeds from 800 to 2100 RPM.



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the torque required to externally run the engine at speeds from 800 to 2100 rpm. The figure shows the normalized motoring torque for various degree of CDA ranging from "6-cylinder" operation (no cylinders deactivated) to "0-cylinder" operation (6 cylinders deactivated - full engine CDA). The figure shows a decreasing motoring torque as more cylinders are deactivated. A 78% reduction in motoring torque is observed at an engine speed of 2100 rpm for full engine CDA.

Full engine CDA could offer utility as part of a fuel saving strategy during vehicle coast. Unlike strategies which disconnect the engine from the drivetrain but leave the engine idling, full engine CDA with connected drivetrain requires zero fuel input. Since there is zero exhaust flow, heat transfer is also eliminated with all cylinders deactivated which can help maintain temperatures during aftertreatment "stay-warm" operation. Full engine CDA is a viable strategy to keep the aftertreatment warm during motoring operation.

Summary

This paper compiles the experimental steady state fuel consumption and aftertreatment thermal management benefits of CDA at different operating conditions. The BTE improvement seen in this and in prior studies are primarily from gains in open cycle and mechanical efficiencies provided by CDA application at low load. These gains result from a reduction in mass rate of air pumped through the engine also increase TOT enabling fuel efficient aftertreatment thermal performance especially at low load operation. Specifically, the findings include:

1. "2-cylinder" and "3-cylinder" enables 3-10% BTE improvement due to increased OCE and CCE and 60 to 120˚C increase in TOT due to lower AFR, when compared to the "6-cylinder best BSFC" strategy at loaded idle operation. "2-cylinder" strategy also achieves similar TOT with 80% lower exhaust flow while being 40% fuel efficient when compared to "6-cylinder warm up" strategy.
2. "2-cylinder" and "3-cylinder" strategies are preferred during warm-up and stay warm operation of the aftertreatment as they have a higher heat transfer rate to the catalyst when compared to the baseline "6-cylinder best BSFC" strategy. "2-cylinder" strategy is preferred over the "6-cylinder warm up" strategy for catalyst bed temperatures above 250˚C due less heat loss from the catalyst bed.
3. During high speed (2200 RPM) low load operating conditions, CDA enables 5-32% BTE improvement depending on load. CDA also enables 100 to 200˚C increase in TOT depending on load thereby enabling fuel efficient aftertreatment thermal management. "6-cylinder best BSFC" strategy warms up the aftertreatment faster for loads between 1.3-3.8 bar BMEP ft-lbs, at catalyst bed temperatures below 100˚C. However CDA warms up faster for catalyst bed temperatures above 100˚C at these loads. The "4-cylinder" strategy will warm-up the aftertreatment system more quickly for loads between 3.8-5.1 bar BMEP ft-lbs at all catalyst bed temperatures.
4. CDA can be used to generate the 500 to 600˚C DPF-inlet temperatures required for particulate matter regeneration with oxygen without the need for a fuel doser, DOC or burner at cruise condition (1200 RPM/7.6 bar BMEP).
5. Full engine CDA enables upto 78% reduction in motoring torque at an engine speed of 2100 rpm and thus could serve as a fuel saving strategy during vehicle coast.

Future Work

1. Study the effects of CDA on different transient drivecycle operating conditions.
2. Combine CDA with other VVA strategies to further improve thermal performance.
3. Study the NVH impact of different CDA strategies.

Nomenclature

A/T - Aftertreatment system
AFR - Air to Fuel Ratio
BMEP - Brake Mean Effective Pressure
BSFC - Brake Specific Fuel Consumption
BTE - Brake Thermal Efficiency
CAC - Charge Air Cooler
CCE - Closed Cycle Efficiency
CDA - Cylinder Deactivation
DOC - Diesel Oxidation Catalyst
DPF - Diesel Particulate Filter
ECM - Engine Control Module
EGR - Exhaust Gas Recirculation
EPA - Environmental Protection Agency
GSI - Generic Serial Interface
HD-FTP - Heavy Duty Federal Test Procedure
LFE - Laminar Flow Element

LVDT - Linear Variable Differential Transformer
ME - Mechanical Efficiency
NOx - Oxides of Nitrogen
NREL - National Renewable Energy Laboratory
NVH - Noise Vibration and Harshness
OCE - Open Cycle Efficiency
PM - Particulate Matter
SCR - Selective Catalytic Reduction
SOI - Start of Injection
TDC - Top Dead Center
TOT - Turbine Outlet Temperature
UHC - Unburnt Hydrocarbons
VGT - Variable Geometry Turbine
VVA - Variable Valve Actuation

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