2018-01-0880 Published 03 Apr 2018

Diesel Engine Cylinder Deactivation for Improved System Performance over Transient Real-World Drive Cycles

Mrunal Joshi, Dheeraj Gosala, and Cody Allen Purdue University-West Lafayette

Sirish Srinivasan Indian Institute of Technology

Aswin Ramesh, Matthew VanVoorhis, Alexander Taylor, Kalen Vos, and Gregory Shaver Purdue University-West Lafayette

James McCarthy Jr Eaton Corp.

Lisa Farrell and Edward D. Koeberlein Cummins Inc.

Citation: Joshi, M., Gosala, D., Allen, C., Srinivasan, S. et al., "Diesel Engine Cylinder Deactivation for Improved System Performance over Transient Real-World Drive Cycles," SAE Technical Paper 2018-01-0880, 2018, doi:10.4271/2018-01-0880.

Abstract

Effective control of exhaust emissions from modern diesel engines requires the use of aftertreatment systems. Elevated aftertreatment component temperatures are required for engine-out emissions reductions to acceptable tailpipe limits. Maintaining elevated aftertreatment components temperatures is particularly problematic during prolonged low speed, low load operation of the engine (i.e. idle, creep, stop and go traffic), on account of low engine-outlet temperatures during these operating conditions. Conventional techniques to achieve elevated aftertreatment component temperatures include delayed fuel injections and over-squeezing the turbocharger, both of which result in a significant fuel consumption penalty. Cylinder deactivation (CDA) has been studied as a candidate strategy to maintain favorable aftertreatment temperatures, in a fuel efficient manner, via reduced airflow through the engine. This work focuses on prediction and demonstration of fuel economy benefits of CDA when implemented at idle and low load portions of the emission certification cycles, such as the heavy duty federal test procedure (HD-FTP), and other real-world drive cycles, including the Orange County bus and port drayage creep cycles. A 3.4% benefit in fuel economy has been demonstrated over the HD-FTP, while maintaining tailpipe-out NOx emissions. Greater improvements in fuel economy have been predicted over the real world cycles, with a 5.6% reduction predicted over the Orange County bus cycle and 35% reduction predicted over the port drayage creep cycle.

Introduction

Diesel engine aftertreatment systems typically consist of a diesel oxidation catalyst (DOC) to oxidize unburnt hydrocarbons (UHC), a diesel particulate filter (DPF) for trapping particulate matter and a selective catalytic reduction (SCR) system for reduction of NOx. The diesel oxidation catalyst "lights-off" at temperatures greater than 200°C [1, 2, 3, 4], thus increasing the rate of oxidation of carbon monoxide (CO) and UHC, while the NOx conversion efficiency of the SCR begins to maximize at temperatures greater than 250°C [5, 6]. It is therefore desirable, in general, to maintain aftertreatment (A/T) component temperatures above 200°C for greater conversion efficiencies.

Real-world engine operation consisting of scenarios like extended idling, large amounts of time spent at low load/low speed conditions and stop-and-go traffic poses a challenge in maintaining desirable A/T component temperatures. Continued use of thermal management techniques like delayed injections [7] and oversqueezed VGT is therefore necessary to generate engine outlet temperatures and exhaust flow rates consistent with reaching and sustaining desirable aftertreatment system temperatures. Utilization of such thermal management techniques generally incurs an increase in fuel consumption; however it is required in order to achieve A/T conversion efficiencies consistent with meeting emission limits.

The Orange County bus cycle is an instance of real-world operation where considerable time is spent at low vehicle speeds, translating to low speed/low load engine operation. Operation of heavy duty trucks at ports consists of extended periods of idle operation and low speed operation. The Heavy Duty Federal Test Procedure (HD FTP), which is a certification cycle for heavy duty engines, consists of nearly 40% of idle operation over the cycle. These are few examples of operation where maintaining desirable aftertreatment temperatures over the entire course of engine operation requires frequent use of fuel-inefficient thermal management strategies.

Diesel Engine Cylinder Deactivation

Cylinder deactivation (CDA) in diesel engines has been studied as a strategy to increase engine outlet temperatures via reduction in air to fuel ratio, which is a result of reduced displaced volume. In addition to reduction in air to fuel ratio, CDA also results in reduced pumping losses as a result of the engine breathing a lower amount of air. Implementation of CDA at low load steady state operating conditions was demonstrated to result in 5-25% improvement in fuel consumption[8], while a combination of CDA with flexible valvetrain strategies like internal EGR and intake valve modulation was experimentally demonstrated to improve the trade off between fuel consumption and thermal management as compared to conventional six-cylinder operation[9].

Reduced exhaust flow rates, combined with sufficiently elevated engine outlet temperatures, are essential to maintain temperature of an A/T system that has already reached desirable temperatures or, is “warmed-up”. CDA is a strategy that can maintain A/T component temperatures on account of its reduced exhaust flow rates. CDA is therefore a fuel-efficient alternative to conventional thermal management strategies, when the focus is to maintain A/T component temperatures (“A/T stay-warm”).

This paper discusses diesel engine cylinder deactivation as a strategy that can be implemented at low speed/low load and idle conditions to maintain desirable aftertreatment component temperatures, thereby improving the trade off between fuel consumption and tailpipe out NOx. Experimental results of implementation of CDA over the HD FTP are discussed, along with predicted fuel consumption benefits over the Orange County bus cycle and the port drayage drive cycle.

Experimental Setup

Experimental data presented here was acquired on an in-line six-cylinder Cummins diesel engine equipped with an electro-hydraulic variable valve actuation (VVA) system. An AC dynamometer enables both steady-state and transient drivecycle testing.

Engine Configuration and Instrumentation

The engine is equipped with a common rail fuel injection system, high pressure cooled exhaust gas recirculation (EGR) and variable geometry turbine (VGT) turbocharging. Figure 1 shows a schematic of the air handling system of the engine.

In-cylinder pressures are acquired for each of the six-cylinders using Kistler 6067C and AVL QC34C pressure transducers through an AVL 621 Indicom module. Fresh air flow into the engine is measured using a laminar flow element. Fuel flow is measured gravimetrically using a Cybermetrix Cyrius Fuel Subsystem (CFS) unit. Intake and exhaust CO_2 concentrations are measured using Cambustion NDIR500 analyzers, allowing for calculation of EGR fraction. A Cambustion fNOx400 fast analyzer is used to measure NOx concentration. CO_2 and NOx concentrations are also measured using California Analytical Instruments NDIR600 and HCLD600 analyzers, respectively. Unburnt hydrocarbons are measured using a CAI HFID600 analyzer.

Coolant, oil and gas temperatures at various locations are measured using thermocouples. Data is monitored and logged through a dSPACE interface. The engine control module (ECM) is connected to the dSPACE system through a generic serial interface (GSI) link that allows cycle-to-cycle monitoring and control of fueling and various other engine functions.

FIGURE 1 Schematic of the air handling system of the engine indicating the positions of relevant actuators and sensors.

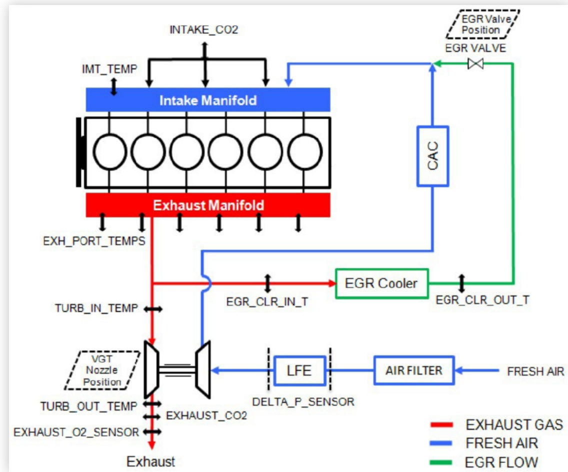
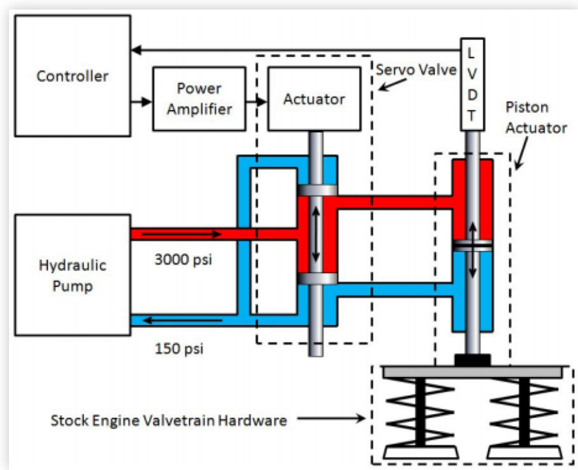


FIGURE 2 Schematic of the variable valve actuation system



Variable Valve Actuation System

A schematic of the VVA system is shown in Figure 2. The electro-hydraulic variable valve actuation (VVA) system allows flexible, cylinder-independent, cycle-to-cycle control of valve operation. Each intake and exhaust valve pair is

FIGURE 3 Deactivated cylinders have no fuel injections and have their valves shut during CDA. The amount of fuel injected doubles for the active cylinders in CDA to be able to meet the required brake torque.

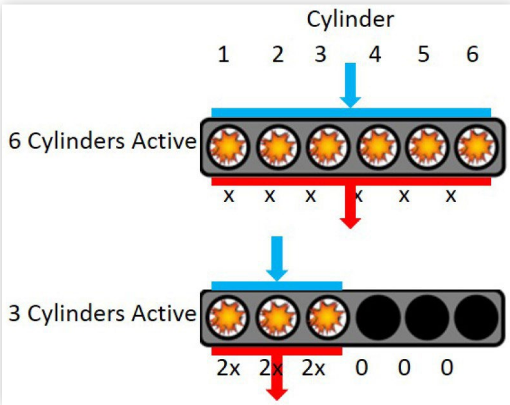
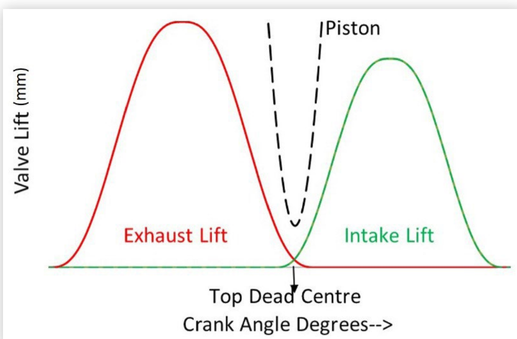


FIGURE 4 Intake and exhaust valve profiles with a conventional cam shaft.



actuated independently. Position feedback for each valve pair is measured using a linear variable differential transformer (LVDT). A real-time controller is implemented in dSPACE to control valve actuation.

Figure 3 shows a cartoon illustrating half-engine CDA operation. Fueling is increased (nearly doubled) in the three activated cylinders (cylinders 1, 2 and 3) to maintain brake torque, while no fuel is injected in the deactivated cylinders (cylinders 4, 5 and 6). Valve motions are also disabled for the deactivated cylinders. Valve profiles for active cylinders in this work are kept the same as stock valve profiles, and are shown in Figure 4.

Aftertreatment System

Figure 5 shows a schematic of the aftertreatment (A/T) system in the test setup. The SCR system in the experimental test bed has been presently set up for passive operation without any urea injection. The A/T system is instrumented with thermocouples at the outlet and inlet of each component. Tailpipe out values of NOx for such passive SCR operation are presently predicted by using an SCR conversion efficiency curve (per Figure 6), measured SCR temperatures and measured engine outlet NOx.

FIGURE 5 A diesel engine aftertreatment (A/T) system consists of discrete emission reducing modules, along with a urea injection system and required instrumentation like thermocouples and emission measurements. Note that the SCR in the test setup is currently used in the passive mode without any urea injection

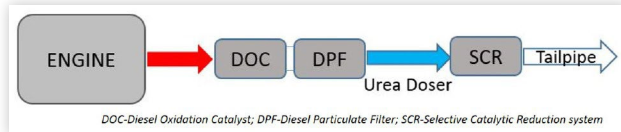
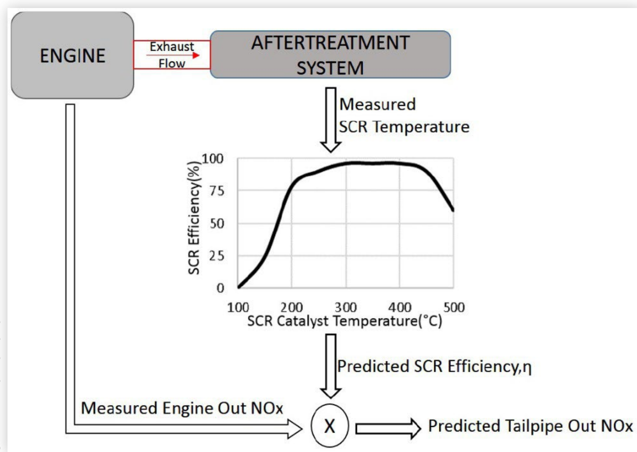


FIGURE 6 Measured SCR temperature from the A/T hardware is used to predict SCR efficiency. The SCR efficiency curve shows that efficiency reaches its maximum value for catalyst temperatures between 250°C and 450°C. Tailpipe out NOx is estimated using this predicted SCR efficiency.



Experimental Results: Impact of Implementing CDA over the HD FTP for an Improved Trade Off between Fuel Consumption and Tailpipe out NOx

Steady State Results of Implementing CDA at Loaded Idle

Figure 7 shows the engine speed and load for the Heavy-Duty Federal Test Procedure (HD FTP), in the form of a cold and hot start sequence as specified by the regulatory emission norms. The net fuel consumption and cumulative tailpipe out NOx emission values over the test sequence are obtained by a weighted summation of their cold start and hot start values - the cold start is weighted by a factor of 1/7 and the hot start is weighted by a factor of 6/7[10].

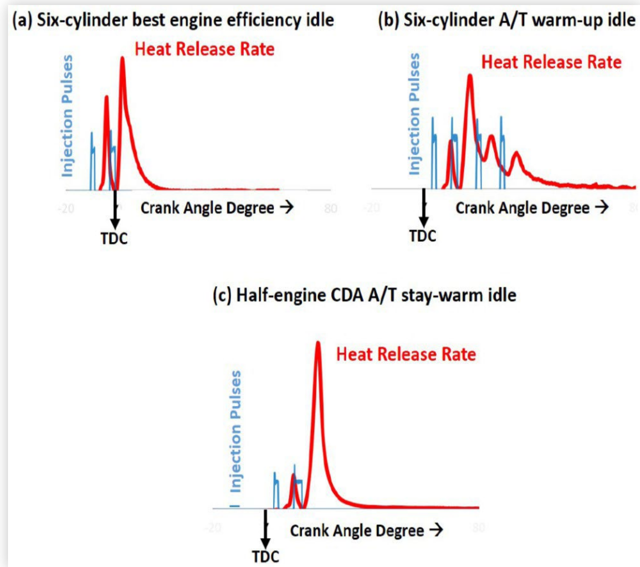
The shaded regions highlight loaded idle sections, and sections where BMEP < 3 bar (as indicated by labels in Figure 7). Furthermore, shaded red bars indicate loaded idle sections in the first 900 seconds of the cold start cycle, which typically correspond to warming-up of the A/T, where A/T component temperatures are below their desirable values. Such sections are henceforth referred to as "warm-up idle sections". Shaded green and brown bars respectively indicate the idle and low load (BMEP < 3 bar) sections of the HD FTP test sequence where A/T component temperatures have reached desirable temperatures. Such sections can also be referred to as "stay-warm sections", and correspond to regions where CDA can be used to maintain desirable A/T component temperatures.

The following paragraph discusses experimentally obtained steady-state results at 800 RPM/1.3 bar to demonstrate the ability of half-engine CDA to maintain A/T temperatures and the reason for this. Results of CDA implementation over the HD FTP test sequence are discussed next.

Injection profiles used for the loaded idle strategies discussed in this section are shown in Figure 8. Figure 8(a) shows two early injections that are close to the top dead center, while Figure 8(b) shows four injections, with the main injection timed relatively further away from TDC. The resulting heat release plays an important role in achieving desirable temperatures at engine outlet. A late heat release also results in increased fuel consumption. Figure 8(c) shows two late injections which are required to obtain certain engine outlet temperatures. The results of using these injection profiles for each strategy are discussed in detail next.

Figure 9 shows the engine outlet temperature vs fuel consumption plot for three different strategies at loaded idle (800 RPM/1.3 bar BMEP). These strategies illustrate the trade off generally incurred between fuel consumption and engine outlet temperatures, and are summarized as follows.

FIGURE 8 At 800 RPM/1.3 bar BMEP, injections closer to the top dead center for (a)"Six cylinder best engine efficiency idle" result in lower fuel consumption, and EOT inconsistent with rapid A/T warm-up. For achieving accelerated A/T warm-up, (b)"Six cylinder A/T warm-up idle" uses four late injections while consuming higher fuel. Two late injections (c) in "Half-engine CDA A/T stay-warm idle" result in EOT consistent with being able to maintain A/T temperatures above 200°C.



1. Six-Cylinder Best Engine Efficiency Idle
   Fuel-efficient engine operation, characterized by low engine outlet temperatures (EOT) and exhaust flow rates which are not suitable for rapid warm-up of A/T components. This strategy uses injections close to the top dead center (per Figure 8(a)) which are consistent with fuel efficiency.

FIGURE 7 For this HD FTP test sequence, shaded red bars indicate idle sections where the A/T has not yet reached desirable temperatures (is not "warmed-up"). Shaded green bars indicate loaded idle sections and shaded brown bars indicate non-idle sections with BMEP < 3 bar; both these regions correspond to A/T having reached temperatures greater than 200°C ("warmed-up").

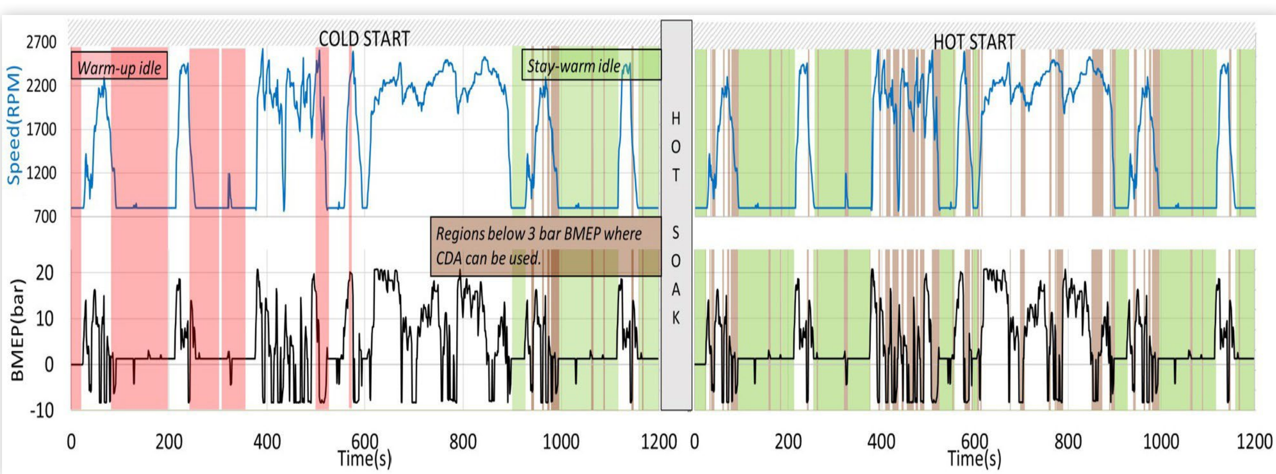
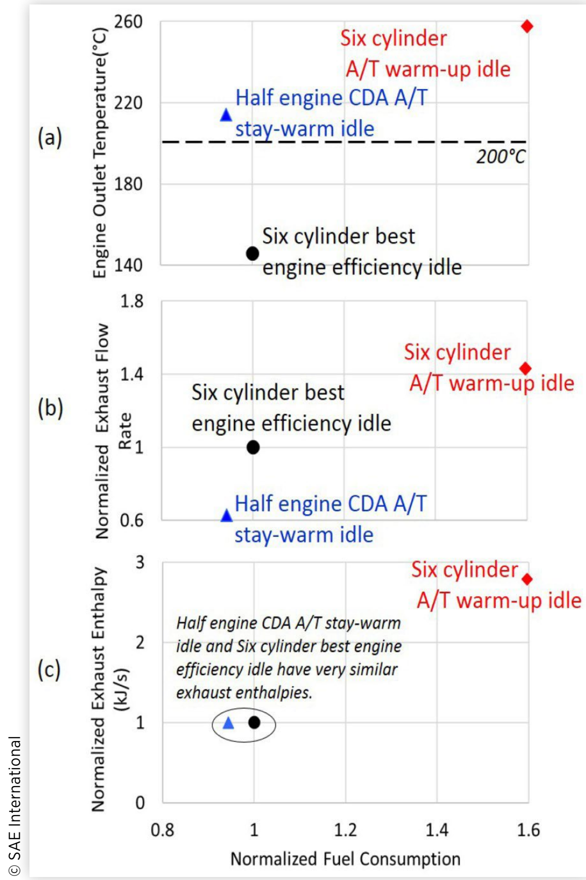


FIGURE 9 Steady state results at 800 RPM/1.3 bar BMEP - Half-engine CDA results in lower exhaust flow rate, and engine outlet temperatures sufficiently elevated to maintain A/T temperatures above 200°C.



2. Six-Cylinder a/T Warm-Up Idle
Engine operation with elevated engine outlet temperatures and exhaust flow rates that are required for rapid warm-up of A/T components. Uses late injections and an oversqueezed VGT in order to obtain elevated EOT, and has nearly 60% higher fuel consumption than the "Six cylinder best engine efficiency idle" strategy. Higher fuel consumption is attributed to late injections and increased back pressure which is a result of oversqueezed VGT operation.
3. Half-Engine CDA a/T Stay-Warm Idle
CDA operation with three out of six cylinders deactivated. This strategy has lower exhaust flow rate (via reduction in displaced volume) and engine outlet temperatures that are sufficiently elevated to maintain desirable temperatures of a warmed-up A/T. Two late injections are used here, along with a relatively less squeezed VGT.

Figure 9(c) shows the exhaust enthalpies for each of the above strategies, calculated using Equation 1.

$$h = \dot{m}_{exh} \times \left(T_{exh} - T_{bed}\right) \tag{1}$$

$\dot{m}_{exh}$ is the engine-outlet gas flow rate, T_{exh} is the engine-outlet gas temperature. Greater EOT and exhaust flow rate results in greater exhaust enthalpy at A/T inlet for "Six-cylinder warm-up idle". "Half-engine CDA stay-warm idle" and "Six-cylinder best engine efficiency idle" have very similar enthalpies as the higher EOT for CDA is offset by lower exhaust flow rate. Exhaust enthalpy is a representation of the energy entering the A/T, and may or may not be directly representative of the capability of a particular strategy in A/T warm-up or A/T stay-warm as this also depends on the temperature of the catalyst bed temperature. Using normalized heat transfer rates is one possible method to do so and is discussed next.

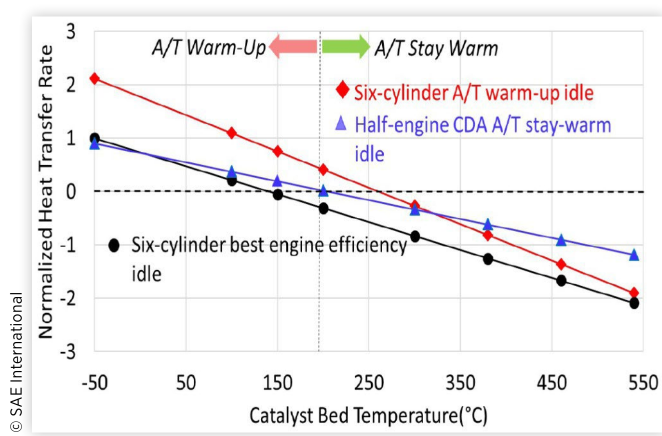
Figure 10 shows normalized heat transfer curves for each of the above strategies. For each strategy, these curves are obtained by using the respective engine outlet temperature and exhaust flow rate, per Equation 2.

$$q = C \times \dot{m}_{exh}^{\frac{4}{5}} \times \left(T_{exh} - T_{bed}\right) \tag{2}$$

where $\dot{m}_{exh}$ is the engine-outlet gas flow rate, T_{exh} is the engine-outlet gas temperature, and C is a constant that depends on the geometry and material of the catalyst.

This equation represents a simplistic model for a lumped A/T system catalyst, and the heat transfer curves indicate, for a certain catalyst bed temperature, the direction and magnitude of heat transfer from the exhaust gas to the catalyst bed. Positive values of rate of heat transfer indicate the catalyst is being heated by the exhaust gas flowing over it, and negative values indicate the exhaust gas is being heated by the catalyst. Therefore, for each strategy, the zero crossing of the heat transfer curve corresponds to its engine outlet temperature - when the catalyst is at the same temperature as engine outlet temperature, no heat transfer occurs between them. The rate at which the lumped catalyst warms-up (gains heat from exhaust gas) or cools down (looses heat to the exhaust gas) is also proportional to the exhaust flow rate. Therefore, for rapid warm-up of the catalyst, both elevated engine outlet temperature and exhaust flow rate are required, whereas once the

FIGURE 10 Normalized heat transfer curves for steady state operation at 800 RPM/1.3 bar BMEP. Elevated EOT and exhaust flow rate leads to fastest rate of A/T warm-up with "Six cylinder A/T warm-up". "Half-engine CDA stay-warm idle" results in the slowest rate of cool-down of the A/T, on account of reduced exhaust flow rate and sufficiently high EOT, and therefore is a fuel-efficient strategy to maintain A/T temperatures as compared to "Six cylinder A/T warm-up".



catalyst has reached desired temperatures, lowered exhaust flow rate and EOT just sufficiently higher than catalyst temperature are desired to maintain those desirable temperatures.

The "Six cylinder A/T warm-up idle" strategy, due to elevated EOT and exhaust flow rate, shows the fastest rate of warm-up of the catalyst as compared to the other two strategies. Lower EOT and exhaust flow rate make the "Six-cylinder best engine efficiency idle" strategy unsuitable for accelerated A/T warm-up.

For catalyst temperatures exceeding 200°C, the rate of cool-down of "Six cylinder A/T warm-up" strategy is, however, greater than that of "Half-engine CDA A/T stay-warm" strategy, and it becomes desirable to use CDA to reduce the rate of cool-down of the catalyst while also achieving a reduction in fuel consumption.

Results over the HD FTP

Figure 11 shows the trade off obtained between fuel consumption and tailpipe out NOx emissions when the strategies discussed above are implemented at loaded idle sections of the HD FTP drive cycle. These results correspond to operation over a cold start and hot start HD FTP, with a twenty minute soak period between the two runs. A description of drivecycle implementation of the above strategies is as follows.

1. Six-Cylinder Best Engine Efficiency Cycle
   Weighted fuel consumption and NOx results corresponding to engine operation over the HD FTP test sequence with the focus on high fuel efficiency. Strategy 1 is used at loaded idle sections of both the cold and hot starts. This implementation is not consistent with meeting emission limits, and provides a baseline for fuel consumption and aftertreatment temperatures.
2. Six-Cylinder a/T Thermal Management Cycle
   Results corresponding to engine operation over the HD FTP with focus on rapid A/T warm-up. These results are representative of the utilization of conventional thermal management techniques: Strategy 2 is used at loaded idle sections, and appropriately delayed injections are used elsewhere, for both the cold and hot starts. As compared to (1), 5% increase in fuel consumption along with 35% lower tailpipe out NOx are obtained. Tailpipe out NOx values for this cycle are consistent with meeting emission regulations.
3. Half-Engine CDA a/T Stay-Warm Idle Cycle
   Results corresponding to utilization of conventional thermal management strategies (delayed injections, oversqueezed VGT) for rapid warm-up during the cold start, followed by utilization of "Half-engine CDA A/T stay-warm idle" strategy at stay-warm loaded idle sections (per shaded green bars in Figure 7). As compared to (2), this operation results in 3% lower fuel consumption, without any penalty in tailpipe out NOx emissions and is an experimental demonstration of the capability of CDA to maintain desirable A/T temperatures, while simultaneously resulting in a decrease in fuel consumption.
4. Half-Engine CDA a/T Stay-Warm Idle/Non-idle Cycle
   Results of (3), modified by including Half-engine CDA operation at stay-warm non-idle sections (<3 bar BMEP) as well. This results in a further 0.4% reduction in fuel consumption, while maintaining tailpipe out NOx emissions levels consistent with emission limits.

FIGURE 11 Up to 3.0% improvement in fuel consumption can be obtained by implementing CDA at loaded idle sections of the HD FTP. Further, 3.4% improvement can be obtained by implementing CDA at appropriate non-idle sections along with loaded idle sections. The ability of CDA to maintain A/T temperature is reflected in the form of nearly equal/lower tail pipe out NOx as compared to "Six-cylinder thermal management".

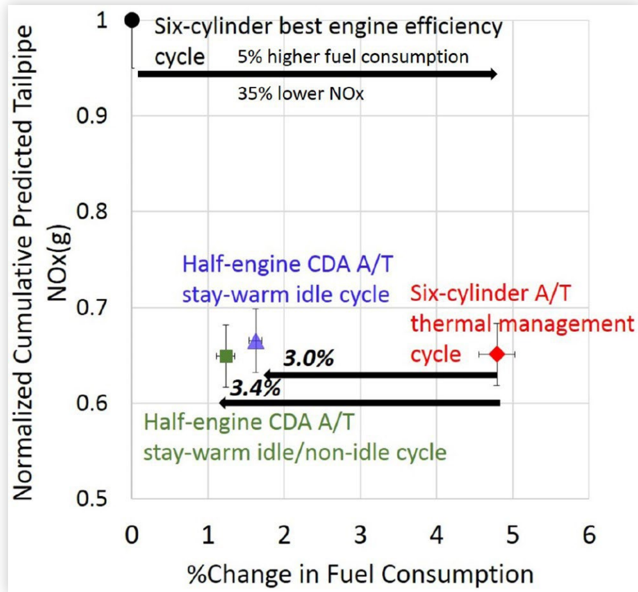
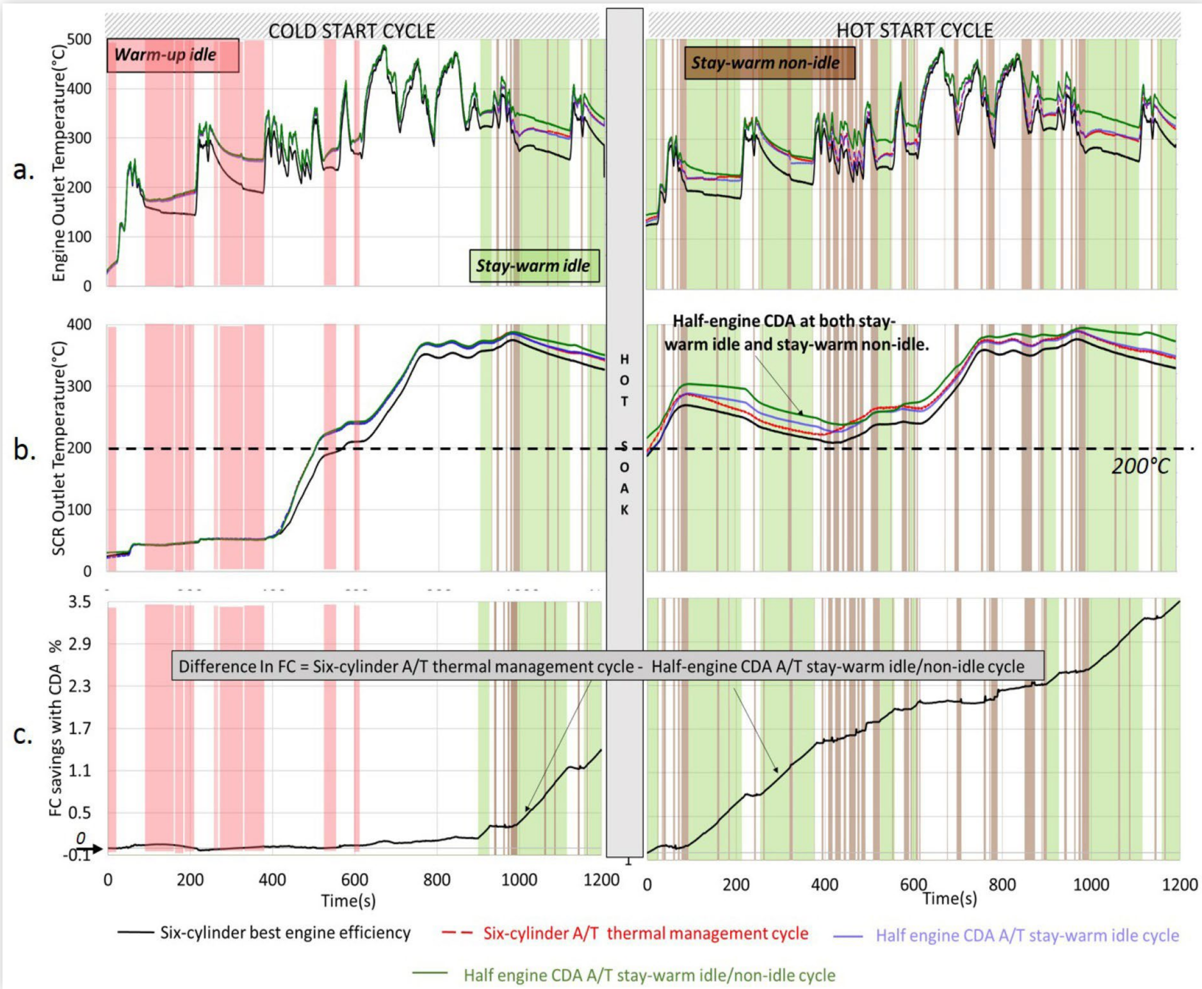


Figure 12(a) shows the engine outlet temperatures, while Figure 12(b) shows the SCR outlet temperatures corresponding to the four cycles discussed above. Figure 12(c) shows that the difference in fuel consumption between "Six cylinder A/T warm-up cycle" and "Half-engine CDA A/T stay-warm idle/non-idle cycle" increases during the shaded green and brown regions, where CDA is implemented. The difference in fuel consumption also remains relatively constant at other regions (non-shaded portions), implying that fuel consumption benefits shown in Figure 11 are indeed due to CDA operation at idle and/or low load stay-warm regions.

Predicted Fuel Consumption Benefits of Implementing Half-Engine CDA over the Orange County Bus Cycle

The Orange County bus cycle is a chassis dynamometer drive cycle representative of operation of urban transit buses in

FIGURE 12 (a,b) The "Six-cylinder A/T thermal management cycle" and "Half-engine CDA A/T stay-warm idle cycle" result in engine-outlet gas temperatures (a), and SCR outlet temperatures (b), that are comparable to each other, and superior to those for the "Six-cylinder best engine efficiency cycle". "Half-engine CDA stay-warm idle/non-idle cycle" results in higher EOT and SCR outlet temperature than the other three cycles. (c) Difference in fuel consumption between "Six-cylinder A/T thermal management cycle" and "Half-engine CDA stay-warm idle/non-idle cycle".



California[11, 12]. The cycle consists of significant portions of low speed/low load operation, wherein maintenance of desirable A/T component temperatures can be a challenge without the use of fuel-inefficient thermal management strategies. The previous section discussed experimental results demonstrating the fuel consumption benefits of CDA observed over the HD FTP while maintaining A/T temperatures. These results were used as a basis to hypothesize similar benefits of CDA over the Orange County bus cycle, if implemented at idle and low load operating conditions.

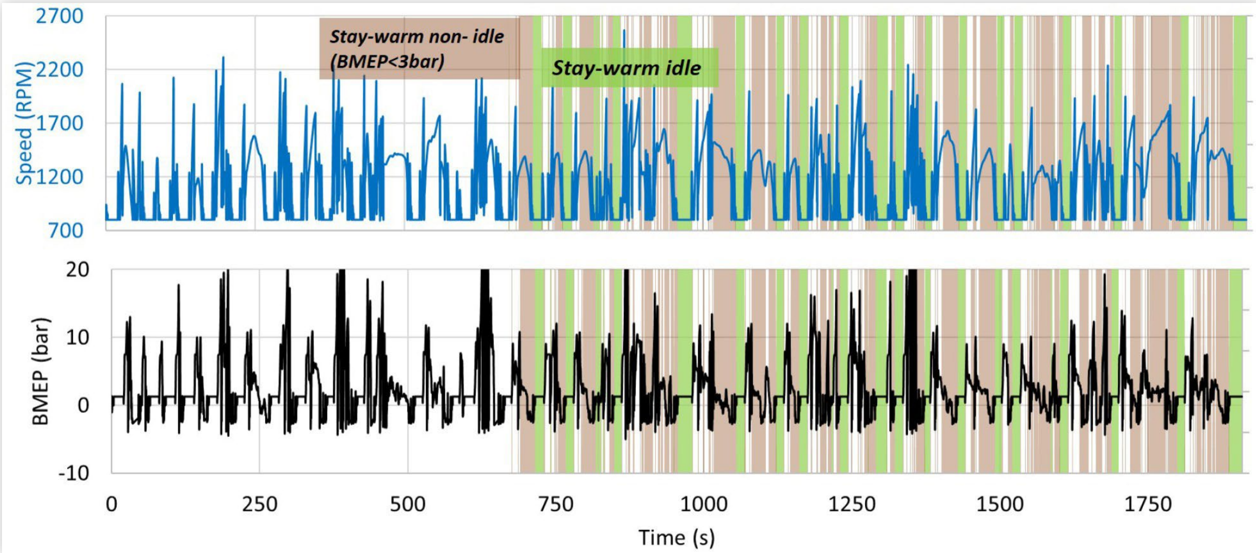
Figure 13 shows the engine speed and load profiles over the Orange County bus cycle. These profiles were generated using the vehicle speed trace as an input to a vehicle system simulation tool, Autonomie[13]. The simulation vehicle used a six cylinder 350 HP diesel engine.

Based on A/T component temperature profiles observed over the HD FTP, it is assumed that the A/T components reach desirable elevated temperatures nearly halfway through the of operation in the Orange County bus cycle. Therefore idle/low load conditions after 750 seconds of the Orange County bus cycle are considered as "stay-warm sections" and have been highlighted to indicate regions where half-engine CDA can be implemented to maintain A/T temperatures.

Approximately 45% of engine operation over the Orange County bus cycle occurs at idle and/or low loads once the A/T has warmed-up (after 750 seconds). The stay-warm idle sections (shaded green bars in Figure 13) correspond to 4.6% of the total drive cycle fuel consumption, while stay-warm low load sections (shaded brown bars in Figure 13, BMEP < 3 bar) correspond to 13.9% of the total drive cycle fuel consumption. Fuel savings via implementation of CDA over stay-warm idle sections of the OCTA are predicted to be 3.8% as compared to utilization of conventional thermal management techniques. Furthermore, implementation of CDA at low load regions where BMEP<3 bar is predicted to result in an additional 0.8% fuel savings, which can be combined with benefits predicted via CDA implementation at idle.

Implementation of half-engine CDA at both stay-warm idle and low load sections of the Orange County bus cycle is therefore predicted to result in 5.6% fuel savings as

FIGURE 13 Engine speed and torque profiles for the Orange County bus cycle, generated by using vehicle speed trace as input to a vehicle system simulation software. The highlighted regions indicate idle/low load sections where CDA can be implemented once the A/T components have reached desirable temperatures (or have "warmed-up").



compared to the continued use of conventional thermal management techniques for maintenance of desirable A/T component temperatures.

Predicted Fuel Consumption Benefits of Implementing CDA at Idle and Low Load Sections of the Port Drayage Drive Cycle

Operation of heavy duty drayage trucks around ports has been characterized by more than one consolidated drive cycle. In an extensive study conducted by the Air Resources Board[14], creep cycles representative of extended idling/low load operation were developed to understand the capability of heavy-duty diesel A/T systems to sustain favorable temperatures, and hence characterize thermal management behavior and emissions over extended idle/low load conditions. Zeng et.al[15] discuss the development of engine cycles over four test modes for heavy heavy-duty engines, based on data collected from real-world operation of these engines and the corresponding vehicles. In another development study, analysis of routes taken by freight trucks around the ports of Los Angeles and Long Beach was used to generate a composite drive cycle for such trucks[16]. The composite drive cycle consists of four modes, which were developed by classifying "vehicle trips", where a trip is defined as a key on to key off event. Certain trip combinations were observed to be more prominent than others both in terms of fuel consumption and operating time.

All of the above mentioned representations of port drayage operation highlight a crucial aspect of port drayage truck operation - the significant amount of time spent at idle, typically as a result of trucks waiting in queues[17, 18]. Based on prior results demonstrating benefits of CDA implementation at idle/low load, CDA implementation at such sections of the port drayage drive cycle can therefor potentially result in similar benefits; i.e. fuel efficient maintenance of desirable A/T component temperatures. In this section, the port drayage drive cycle developed by NREL[16] is considered in order to identify idle/low load operating regions where CDA can be implemented for improved fuel consumption and similar A/T thermal performance.

Figure 14 shows the engine speed and load profiles obtained by using the composite port drayage drive cycle developed by NREL as an input to a vehicle system simulation software. In order to obtain the engine speed/load from the vehicle speed trace, a 10.8 L 330HP Cummins ISM engine was used in the simulation software.

The composite cycle developed in this study consists of four modes, as shown in Figure 15. The creep mode (Figure 15a) is representative of very low speed operation, typical of operation in truck queues. The port/near dock mode (Figure 15b) consists of low speed operation, typical of on-dock movement. Local mode (Figure 15c) represents operation that achieves high peak speeds but does not sustain these speeds and is typical of travel on regional roads, driving in traffic or brief travel on freeways. The high speed cruise (Figure 15d) represents high speed operation with sustained high speeds, typical of travel on freeways. It is not necessary for real-world drayage operation to follow any specific order of these modes, although certain driving patterns have been found to be more frequent that others.

Figures 15(a-d) highlight operating conditions corresponding to idle and low load for each mode of the NREL composite port drayage drive cycle. These are regions where

FIGURE 14 Engine speed and torque profiles for the NREL composite port drayage drive cycle, obtained by using vehicle speed trace as an input to a vehicle system simulation software.

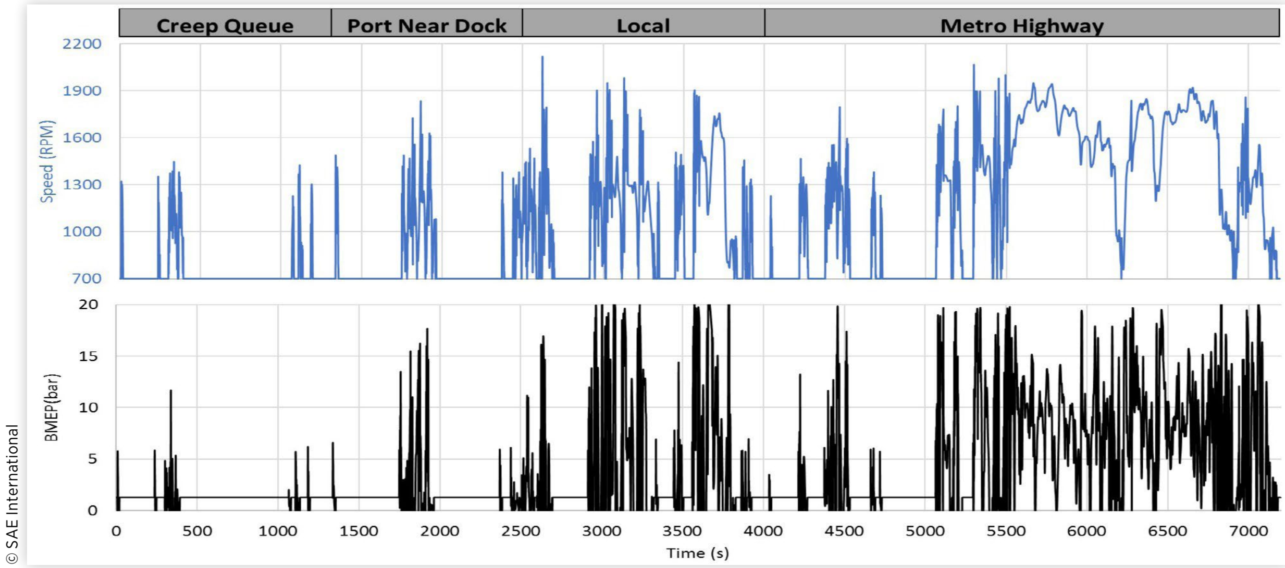


FIGURE 15 Engine speed and torque profiles for each mode of the NREL composite port drayage drive cycle. Shaded green bars indicate idle portions, while shaded brown bars indicate non-idle portions below 3 bar BMEP where half-engine CDA can be implemented for improved fuel efficiency while maintaining desired A/T component temperatures.

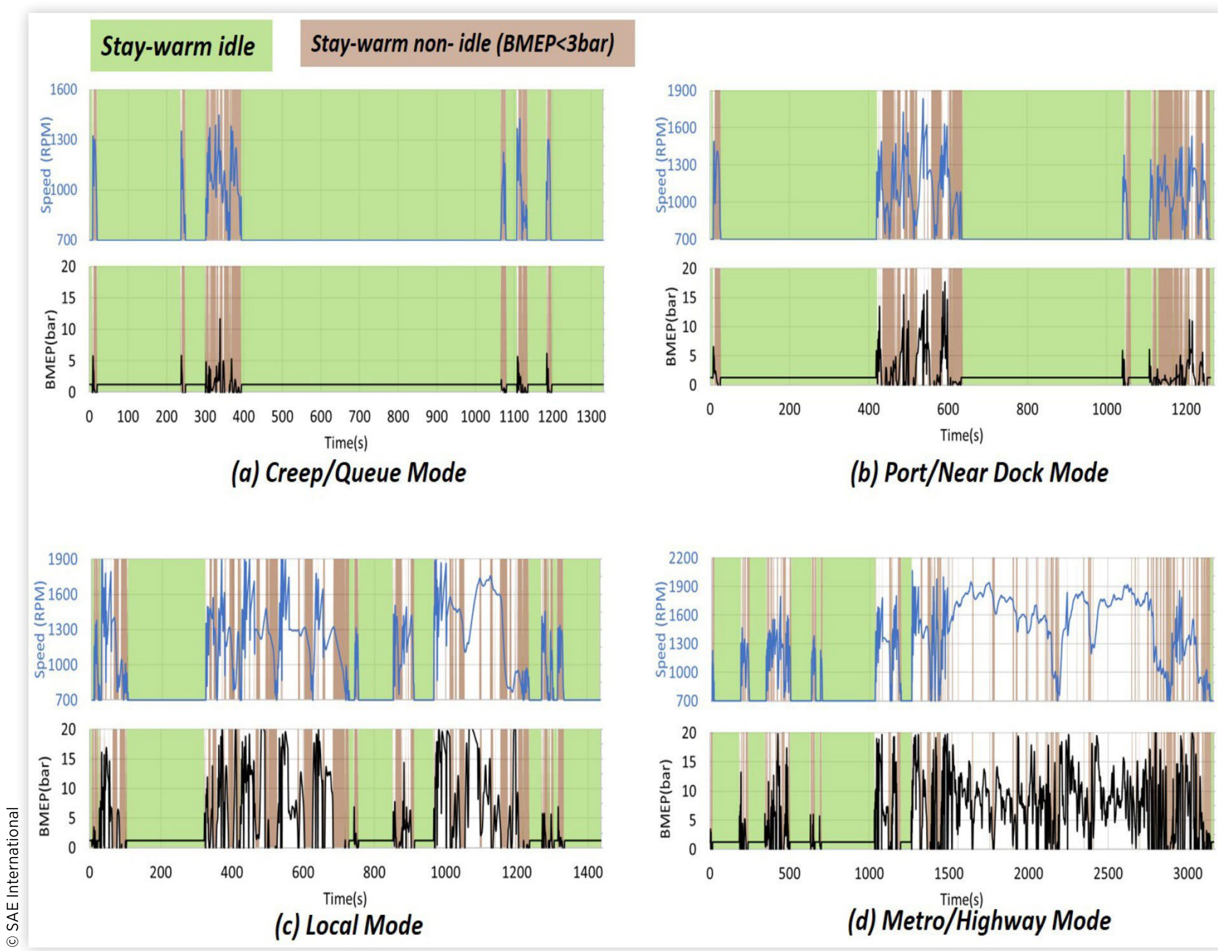


TABLE 1 Predicted fuel savings by implementation of half engine CDA at idle and low loads of modes of the Port Drayage Creep cycle

Mode	Fuel Savings, %
Creep/Queue	35%
Port/Near Dock	21.2%
Local	10.6%
Highway	4%

half-engine CDA can potentially be implemented. Fuel savings that can be so obtained are predicted in a manner analogous to the Orange County bus cycle. These predictions are based on an assumption that the A/T system is already warmed-up prior to a period of extended idling/low load operation, such that CDA operation at appropriate sections can follow to maintain the A/T temperatures. This assumption is considered reasonable as vehicle operation is generally not limited to any specific order of the modes in Figure 15. An example of such operation (where the A/T is warmed-up) is highway truck operation (in cruise mode, represented by Figure 15(d)) while carrying a load, followed by waiting in queues at the port (creep/queue mode, represented by Figure 15(a)). Moreover, considering that 69% of drayage truck operation occurs within a 40 mile radius with multiple trips (port/near dock mode represented by Figure 15(b)), a truck can be considered to have several "hot start" near-dock like cycles, where in half-engine CDA can be implemented for several of the hot-starts.

Table 1 shows the predicted fuel savings that can be obtained by implementing half-engine CDA at idle/low load sections for each mode of the composite cycle shown in Figure 14.

As expected, CDA is predicted to have highest fuel consumption benefits (35%) over the Creep/Queue cycle if implemented at stay-warm idle/low load sections. Upon implementation across the other modes, which have successively decreasing amount of idle/low load operation, fuel savings of 21%, 10% and 4% are predicted respectively.

Conclusion

Table 2 summarizes the experimental and predicted fuel consumption benefits obtainable for via implementation of CDA over different drive cycles.

Cylinder deactivation is a fuel-efficient strategy to maintain desirable A/T component temperatures for drive cycles consisting of significant idle and low load operation. Over the HD FTP, a 3.4% reduction in fuel consumption (over conventional thermal management operation) was experimentally demonstrated. Half-engine CDA implemented at idle/low load regions of the Orange County bus cycle is predicted to result in 4.3% reduction in fuel consumption. Implementation of CDA over the port drayage drive cycle, on account of significant idling durations, is predicted to result in fuel consumption benefits ranging from 4% to 35% across different modes of the drive cycle.

TABLE 2 Summary of fuel savings obtainable by implementation of half-engine CDA at idle and low loads

Drivecycle	Fuel Savings, %
HD FTP	3.4% (Experimental)
Orange County bus cycle	5.6% (Predicted)
Port Drayage Creep cycle	4% - 35% (Predicted)

Future Work

Deactivating greater number of cylinders is hypothesized to result in similar/improved thermal management performance, and its implementation over the transient test sequences constitutes the future work in the effort to improve the trade off between fuel consumption and tail pipe out NOx emissions.

Nomenclature

A/T - Aftertreatment system
BMEP - Brake Mean Effective Pressure
CAC - Charge Air Cooler
CDA - Cylinder Deactivation
DOC - Diesel Oxidation Catalyst
DPF - Diesel Particulate Filter
ECM - Engine Control Module
EGR - Exhaust Gas Recirculation
EOT - Engine Outlet Temperature
EPA - Environmental Protection Agency
GSI - Generic Serial Interface
HD-FTP - Heavy Duty Federal Test Procedure
LFE - Laminar Flow Element
LVDT - Linear Variable Differential Transformer
NOx - Oxides of Nitrogen
NREL - National Renewable Energy Laboratory
SCR - Selective Catalytic Reduction
TDC - Top Dead Center
UHC - Unburnt Hydrocarbons
VGT - Variable Geometry Turbine
VVA - Variable Valve Actuation

References

[1] Charlton, S., Dollmeyer, T., and Grana, T., "Meeting the US Heavy-Duty EPA 2010 Standards and Providing Increased Value for the Customer," *SAE Int. J. Commer. Veh.* 3(1):101-110, 2010, doi:10.4271/2010-01-1934.

[2] Blakeman, P., Chiffey, A., Phillips, P., Twigg, M. et al., "Developments in Diesel Emission Aftertreatment Technology," SAE Technical Paper 2003-01-3753, 2003, doi:10.4271/2003-01-3753.

[3] Song, X., Surenahalli, H., Naber, J., Parker, G. et al., "Experimental and Modeling Study of a Diesel Oxidation Catalyst (DOC) under Transient and CPF Active Regeneration Conditions," SAE Technical Paper 2013-01-1046, 2007, doi:10.4271/2013-01-1046.

[4] Stanton, D., Charlton, S., and Vajapeyazula, P., "Diesel Engine Technologies Enabling Powertrain Optimization to Meet U.S. Greenhouse Gas Emissions," *SAE Int. J. Engines* 6(3):1757-1770, 2013, doi:10.4271/2013-24-0094.

[5] Byrne, J., Chen, J., and Speronello, B., "Selective Catalytic Reduction of NOx Using Zeolitic Catalysts for High Temperature Applications," *Catalysis Today* 13(1):33-42, 1992.

[6] Lambert, C., Hammerle, R., McGilland, R., and Khair, M., "Technical Advantages of Urea SCR for Light-Duty and Heavy-Duty Diesel Vehicle Applications," SAE Technical Paper 2004-01-1292, 2004, doi:10.4271/2004-01-1292.

[7] Stadlbauer, S., Waschl, H., Schilling, A., and del Re, L., "DOC Temperature Control for Low Temperature Operating Ranges with Post and Main Injection Actuation," SAE Technical Paper 2013-01-1580, 2013, doi:10.4271/2013-01-1580.

[8] Ramesh, A., Shaver, G., Allen, C., Gosala, D. et al., "Utilizing Low Airflow Strategies, Including Cylinder Deactivation, to Improve Fuel Efficiency and Aftertreatment Thermal Management," *International Journal of Engine Research* 1:1, 2017, doi:10.1177/1468087417695897.

[9] Ding, C., Roberts, L., Fain, D.J., Ramesh, A.K. et al., "Fuel Efficient Exhaust Thermal Management for Compression Ignition Engines during Idle Via Cylinder Deactivation and Flexible Valve Actuation," *International Journal of Engine Research* 1, 2015, doi:10.1177/1468087415597413.

[10] United States Environmental Protection Agency, "Electronic Code of Federal Regulations," cfr 2015 title 40 vol 33 sec 1065.512, 2015.

[11] Kelly, K., Prohaska, R., Ragatz, A., and Konan, A., "Nrel Drivecat-Chassis Dynamometer Test Cycles," 2016.

[12] Wayne, S., Clark, N., Nine, R., and Elefante, D., "A Comparison of Emissions and Fuel Economy from Hybrid-Electric and Conventional-Drive Transit Buses," *Energy and Fuels* 18(1):257-270, 2004.

[13] Argonne National Labs and General Motors.

[14] Sharp, C., Neely, G., Webb, C., and Smith, I., "Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles," 2017.

[15] Zhen, F., Clark, N., Bedick, C., Gautam, M. et al., "Development of a Heavy Heavy-Duty Diesel Engine Schedule for Representative Measurement of Emissions," *Journal of the Air and Waste Management Association*, 2009.

[16] Prohaska, R., Konan, A., Kelly, K., and Lammert, M., "Heavy-Duty Vehicle Port Drayage Drive Cycle Characterization and Development," 2016.

[17] Couch, P. and Leonard, J., "Characterization of Drayage Truck Duty Cycles at the Ort of Long Beach and Port of los Angeles," 2011.

[18] Papson, A. and Ippoliti, M., "Key Performance Parameters for Drayage Trucks Operating at the Ports of los Angeles and Long Beach," 2013.

ISSN 0148-7191