DIESEL DYNAMIC SKIP FIRE (dDSF™)
Simultaneous CO_2 and NO_x Reduction

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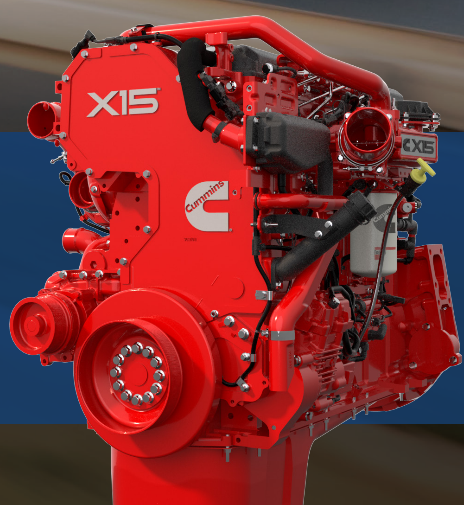
Gleichzeitige CO_2- und NO_x-Reduzierung



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Abstract

Reductions in CO_2 and NO_x tailpipe emissions present conflicting challenges for diesel engines as worldwide standards continue to become more stringent. Dynamic Skip Fire (DSF®), in production on SI V8 engines, has potential in diesel commercial vehicles as dDSF to provide benefits in reducing both CO_2 and NO_x emissions simultaneously.

DSF is an advanced cylinder deactivation technology which enables any number of cylinders to be dynamically selected to operate on an event by event basis. Noise, vibration and harshness (NVH) is proactively mitigated by manipulating the firing sequence and cylinder loading to avoid vehicle resonances.

Cummins and Tula embarked on a development project to demonstrate the benefits of dDSF technology for diesel engines in commercial vehicle applications to reduce emissions and control NVH. The development work has been carried out on a 15-liter Cummins X15 6-cylinder diesel engine. The engine and controller have been modified to integrate Tula's Dynamic Skip Fire control algorithms, to command combustion or deactivation, on a cylinder event basis. Test data has been collected on a wide range of steady-state conditions which was used to evaluate transient operation in simulation. Evaluations of CO_2 and NO_x tailpipe emissions benefits have been conducted on both a Heavy-Duty FTP test cycle and the Low-Load Cycle (LLC #7) proposed by California Air Resources Board (CARB) for their upcoming rulemaking. dDSF is under development for possible future product application. Further work is required to determine whether the technology can meet durability, reliability and cost targets for future products.

On the HD FTP cycle, dDSF technology modeling predicted reductions of NO_x emissions by 45% while simultaneously reducing CO_2 by 1.5%. On the proposed LLC #7, dDSF technology modeling predicted reductions of tailpipe NO_x emissions by 66% while simultaneously reducing by CO_2 by 4%. Further reductions in NOx emissions should be achievable with the addition of increased conventional thermal management over the cycles with a reduction in the CO_2 benefit. The reduction of tailpipe NO_x is achieved primarily by optimized exhaust temperature control, resulting in improved conversion efficiency of the Selective Catalytic Reduction after-treatment system. The CO_2 reductions are achieved primarily through reductions in pumping losses. Cylinder deactivation thus allows for additional trade-off opportunities for reductions of CO_2 and NO_x emissions.

Kurzfassung

Vor dem Hintergrund der sich weltweit weiter verschärfenden Abgasgrenzwerte sind die gleichzeitige Reduzierung der CO_2- und der NO_X-Emissionen gegenläufige Anforderungen für Dieselmotoren. Dynamic Skip Fire (DSF®) ist bei V8-Ottomotoren bereits im Großserieneinsatz und hat als dDSF das Potential, bei Nutzfahrzeug-Dieselmotoren die CO_2-und NO_X-Emissionen gleichzeitig zu verbessern.

DSF ist eine weiterentwickelte Zylinderdeaktivierungs-Technologie, bei der jede beliebige Anzahl von Zylindern dynamisch von Zyklus zu Zyklus gezündet werden kann. Durch die Beeinflussung der Zündfolge und der Zylinderlast werden die Fahrzeug-Eigenfrequenzen vermieden und die Auswirkungen auf das NVH-Verhalten (Noise, Vibration and Harshness) minimiert.

Cummins und Tula haben ein Entwicklungsprojekt gestartet, um das Verbesserungspotential von dDSF für Nfz-Dieselmotoren hinsichtlich der Abgasemissionen bei akzeptablem NVH-Verhalten zu demonstrieren. Die Entwicklungsarbeiten wurden an einem 15 l Cummins X15 6-Zylinder-Dieselmotor durchgeführt. Der Motor und die Elektronik wurden modifiziert, um Tulas Dynamic Skip Firing Regelalgorithmen zu integrieren, so dass von Zylinder zu Zylinder und von Zyklus zu Zyklus die einzelnen Arbeitsspiele gezündet oder deaktiviert werden können. Die Versuchsergebnisse wurden, basierend auf umfangreichen stationären Untersuchungen, ermittelt. Anhand dieser Daten wurde das dynamische Verhalten simuliert. Es wurden Untersuchungen durchgeführt, um anhand des Heavy-Duty FTP-Zyklus und einem von der CARB (California Air Resources Board) für die zukünftigen Grenzwerte zusätzlich vorgeschlagenen Schwachlast-Zyklus (Low Load Cycle-LLC #7), die Vorteile bezüglich der CO_2- und der NO_X-Emissionen zu ermitteln. dDSF ist in Entwicklung für zukünftige Produktanwendungen. Weitere Untersuchungen sind notwendig um festzustellen, ob diese Technologie die Anforderungen an zukünftige Produkte hinsichtlich Haltbarkeit, Zuverlässigkeit und Kosten erfüllt.

Beim HD FTP-Zyklus konnten durch die Simulation der dDSF-Technologie eine Reduzierung der NO_X-Emissionen um 45% und eine gleichzeitige Reduzierung der CO_2-Emissionen um 1,5% vorhergesagt werden. Bei dem vorgeschlagenen Schwachlast-Zyklus (LLC #7) wurde durch die Simulation eine Reduzierung der NO_X- um 66% und gleichzeitig der CO_2-Emissionen um 4% ermittelt. Eine weitere Reduzierung der NO_X-Emissionen kann durch eine zusätzliche gesteigerte konventionelle Aufheizstrategie erreicht werden. Dadurch werden allerdings die CO_2-Vorteile reduziert. Die Reduzierung der NO_X-Emissionen erfolgt im Wesentlichen durch ein optimiertes Abgastemperatur-Management und eine daraus resultierende verbesserte Konvertierungsrate des Selective Catalytic Reduction (SCR)–Abgasnachbehandlungs-Systems. Die Reduzierung der CO_2-Emissionen wird hauptsächlich durch eine Reduzierung der Ladungswechselverluste erreicht. Durch die Zylinderdeaktivierung können somit die Verbesserungen zweier normalerweise gegenläufiger Anforderungen kombiniert werden.

Introduction

There is worldwide pressure to reduce emissions from heavy-duty commercial vehicles which account for a significant portion of CO_2 and NO_x emissions from mobile source applications. The California Air Resources Board is developing its Omnibus Low NO_x regulations. These regulations focus on a 90% NO_x reduction on current certification cycles, combined with a new Low Load Cycle that emphasizes specialized use cases relevant to low load operation. In addition, the emissions useful life and warranty coverage likely will be proposed to be extended, and a new in-use test program is expected to be proposed. US EPA is also developing new Low NO_x regulations under its Cleaner Trucks Initiative and is evaluating similar program elements as the California Air Resources Board. In parallel, the European Union has recently passed EU HDV CO_2 regulations requiring a 15% reduction in CO_2 emissions from select heavy-duty vehicles by 2025 and 30% by 2030, while still maintaining current stringencies on NOx and other emissions standards.

Cummins, Inc. is a leader in powertrain development for the commercial vehicle market. Cummins, Inc. is continuously evaluating technologies that will assist meeting future regulations and customer demands. Cylinder deactivation is a technology that has shown the ability to improve fuel consumption in turbo-charged diesel engines through the efficient reduction of pumping work. The reduction in air flow simultaneously increases engine exhaust temperatures at low torque which has the benefit of increasing aftertreatment temperatures and conversion efficiency of the selective catalytic reduction (SCR) system used for NO_x control on the X15 heavy-duty diesel engine system. Tula Technology's Diesel Dynamic Skip Fire (dDSF) controls engine cylinder deactivation on an event-by-event basis to optimize exhaust temperature, fuel consumption, transient performance, and NVH. In order to assess dDSF for application on commercial vehicles, Cummins and Tula are collaborating under a joint development program to apply this technology to commercial vehicle applications.

In this development program, Cummins and Tula are implementing dDSF in a heavy duty tractor application for both real world driving and performance assessments. NVH mitigation through the use of dDSF is expected and will be demonstrated in the final testing phase of the collaboration. Dynamometer testing on key certification cycles will also be a part of the final testing phase. Current progress has produced a dDSF calibration that mitigates NVH to begin vehicle-level testing, assess steady-state performance changes and simulate transient cycle emissions improvement. Development will continue to optimize performance and emissions in a vehicle demonstration.

Dynamic Skip Fire

The advantages of Dynamic Skip Fire for light duty applications have been established, and DSF is in production on light duty gasoline engines, improving upon the fuel consumption and aftertreatment control compared to more traditional cylinder deactivation systems.[1][2] DSF improves the flexibility of engine control by eliminating the direct connection between crankshaft speed and firing events. Engine output is controlled primarily by selectively firing only a subset of possible combustion events. In practice, this control allows for optimization of every cylinder event. The basic operation is shown in figure 1 for transient operation.

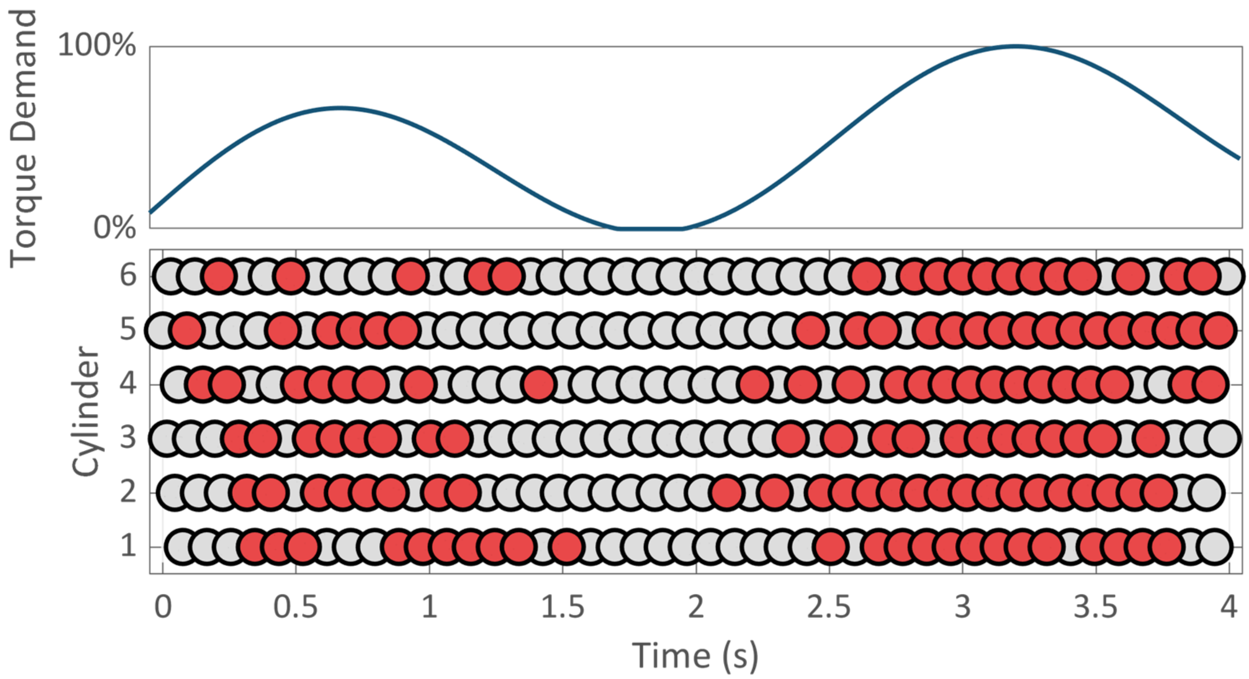

Figure 1: DSF in Transient Operation

In real driving, conditions that are constant for more than a few seconds can be rare. But when these conditions are found, the dDSF algorithm will select between approximately 10-30 cyclically generated patterns, 11 of which are shown in figure 2. Use of these patterns optimizes the tradeoff between fuel consumption, exhaust temperature, occupant comfort, and other parameters.

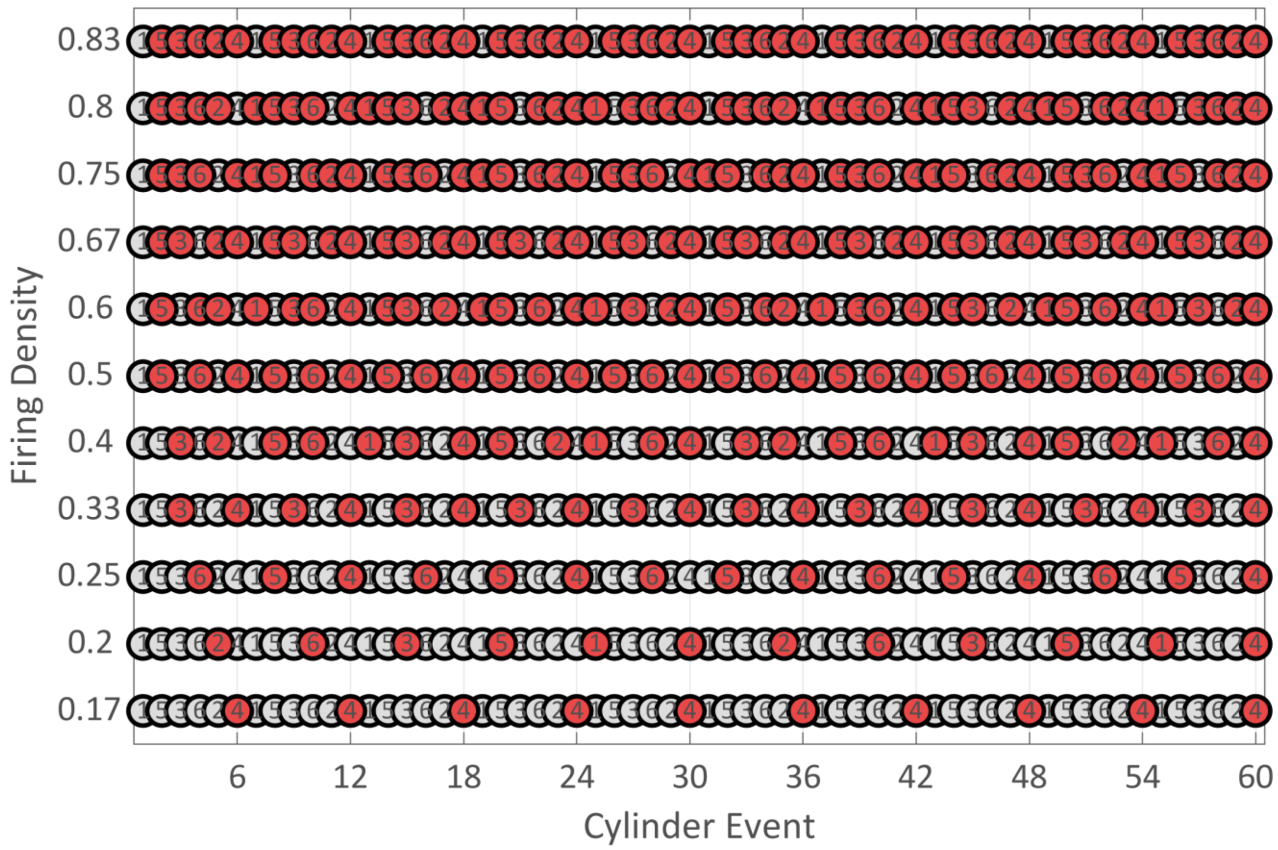

Figure 2: Selected Steady State Firing Patterns

Cummins and Tula Collaboration

In prior work, Cummins has conducted a large number of experiments with more conventional cylinder deactivation, in conjunction with Purdue and Eaton.[3][4] Similarly, and building on conventional cylinder deactivation, Tula and FEV have projected the advantages made possible by dDSF.[5][6] Building on this work as leaders in diesel powertrain development and cylinder deactivation optimization, respectively, Cummins and Tula are collaborating to improve upon prior work and produce the optimal cylinder deactivation strategy for diesel engines.

The dDSF technology dramatically improves tailpipe NO_x emissions by allowing algorithmic control of exhaust temperature, which is independent of requested torque. Fundamentally, this technology enables the aftertreament system to remain effective in NO_x conversion over a broader range of operating conditions and duty cycles. Simultaneously, dDSF reduces fuel consumption by decreasing the pumping work of the system.

Cummins X15 Engine

In order to demonstrate the potential of dDSF on a state-of-the-art engine, the X15 efficiency series engine (shown in figure 3) was selected to be fitted with a deactivating valvetrain and dDSF algorithms. The X15 engine combines broad market penetration with best in class fuel consumption. Delivering up to 373 kW (500 hp) and 2508 Nm (1850 lb-ft) torque, the X15 combines industry leading fuel efficiency and superior performance. The X15 is a 6-cylinder engine with a variable geometry turbocharger, XPI high pressure common rail fuel system, and a high pressure exhaust gas recirculation (EGR) system. Additional emissions control is performed with the aftertreatment system which consists of a DOC/DPF and an SCR catalyst. The hardware used for deactivating the valvetrain components was sourced from Jacobs Vehicle Systems (JVS).

Figure 3: Cummins X15 Engine

Diesel Dynamic Skip Fire Technology

Algorithm and Implementation

Cylinder deactivation offers dramatic advantages to diesel engines, but the implementation requires careful analysis of the control strategy. Initial calibrations for engine operation under DSF are similar to a cylinder undergoing combustion at equivalent per-event indicated mean effective pressure (IMEP).

A diagram showing the dDSF integration is shown in figure 4. Highlighted are functions that are impacted by dDSF and need to be addressed prior to production. In particular, EGR and fuel scheduling are generally modified to ensure acceptable in-cylinder combustion. On board diagnostics need to be cognizant of intentionally deactivated events. Control of deactivation and reactivation of cylinders is done to simultaneously manage aftertreatment temperature for improved NO_x conversion and reduced fuel consumption.

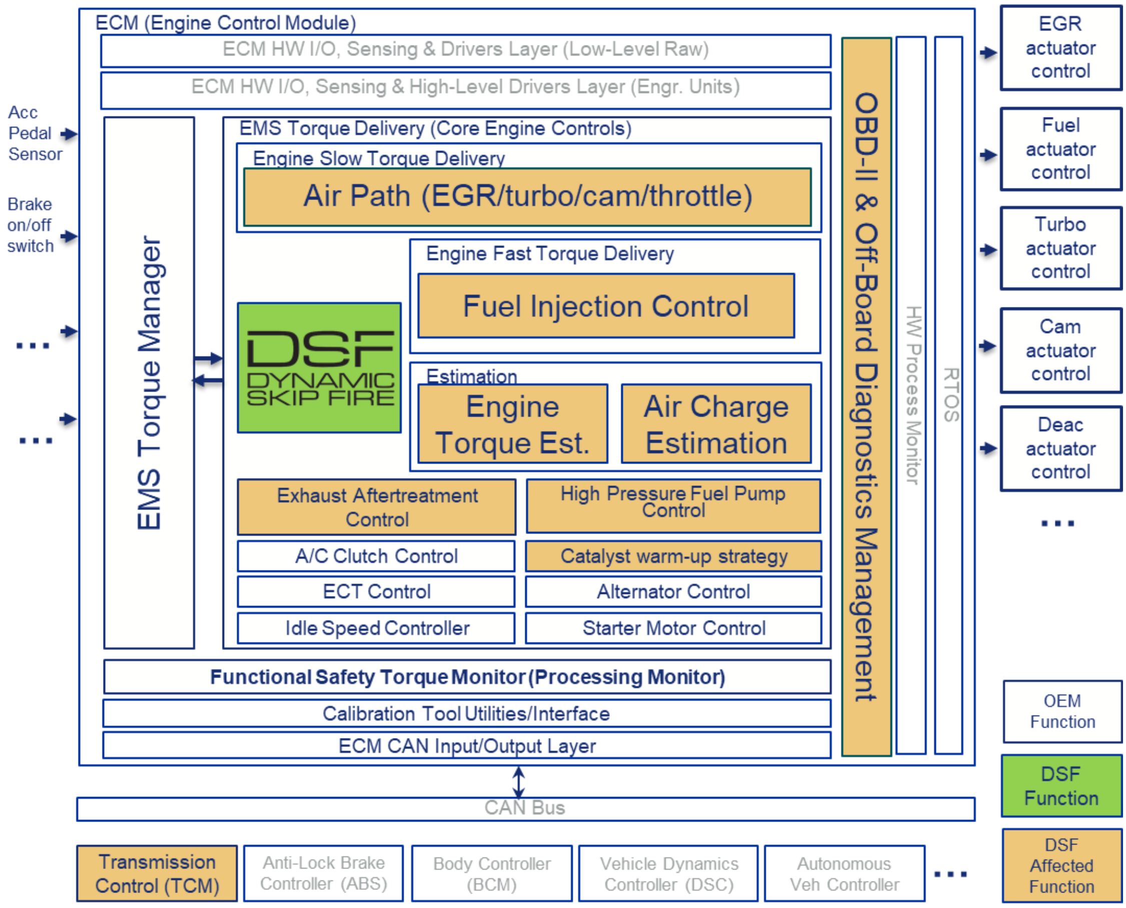

Figure 4: Integration of DSF algorithm into Diesel Control Algorithms

Advantages of Dynamic Skip Fire on Diesel Engines

Steady State Engine Dynamometer Experimental Results

Steady state mapping was performed to assess the relationship between performance parameters, emissions parameters, and firing fraction of the combustion events. The mapping focused on levels below 4 bar brake mean effective pressure (BMEP). This load level corresponds to thresholds where dDSF enables improved fuel efficiency and exhaust temperatures tradeoffs, as well as the approximate cutoff for acceptable NVH in vehicle testing. Initial testing used current calibration settings for the high pressure common rail fuel system commands as well as air flow and EGR levels. Minor adjustments were made to those commands to account for changes in cylinder combustion conditions. The results presented here are based on those preliminary modifications and full optimization of the performance calibration is planned under the joint development program.

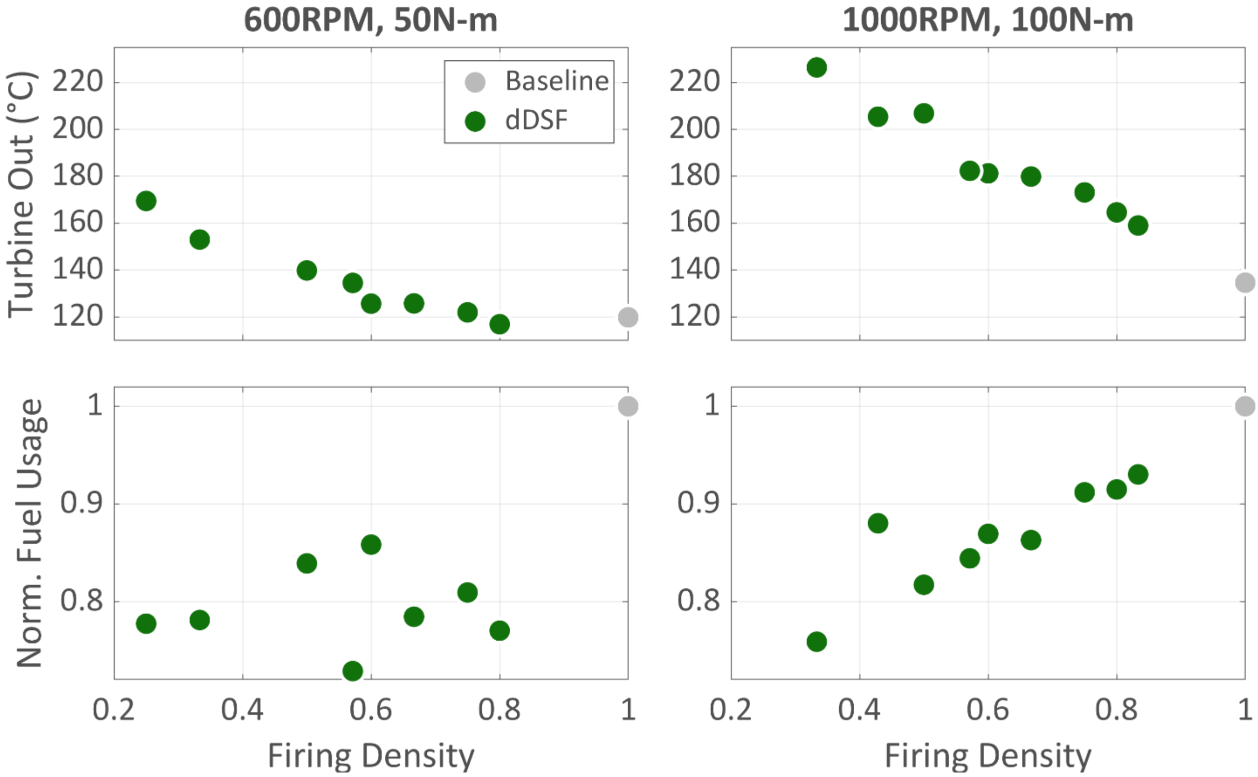

Figure 5: Turbine Outlet Temperature and Fuel Usage as a function of firing fraction for Low and High Idle Engine Speeds

Figure 5 compares the key tradeoffs between fuel consumption and turbine outlet temperature as a function of commanded firing fraction using dDSF technology. Two key conditions are highlighted, a low idle speed low load point 600 RPM, 50 N-M and a high idle speed low load condition 1000 RPM, 100 N-m. These are challenging conditions during low load duty cycle operation for maintaining after-treatment temperature conditions with a turbo-charged diesel engine. At 600 RPM, a 20% fuel consumption improvement is realized while increasing exhaust temperatures by 40ºC. Further tradeoffs between fuel consumption and exhaust temperature can be made in future iterations if higher turbine outlet temperatures are required during vehicle operation. At 1000 RPM, dDSF shows an increase in exhaust temperature of nearly 100ºC while still improving fuel consumption by 25%.

Figure 6 shows that for two different steady-state conditions, a significant decrease in fuel consumption was achieved with a corresponding increase in turbine outlet temperature, as firing fraction was reduced for the same conditions. Under those conditions, simultaneous exhaust temperature and CO_2 improvements can be dramatically improved with the use of dDSF.

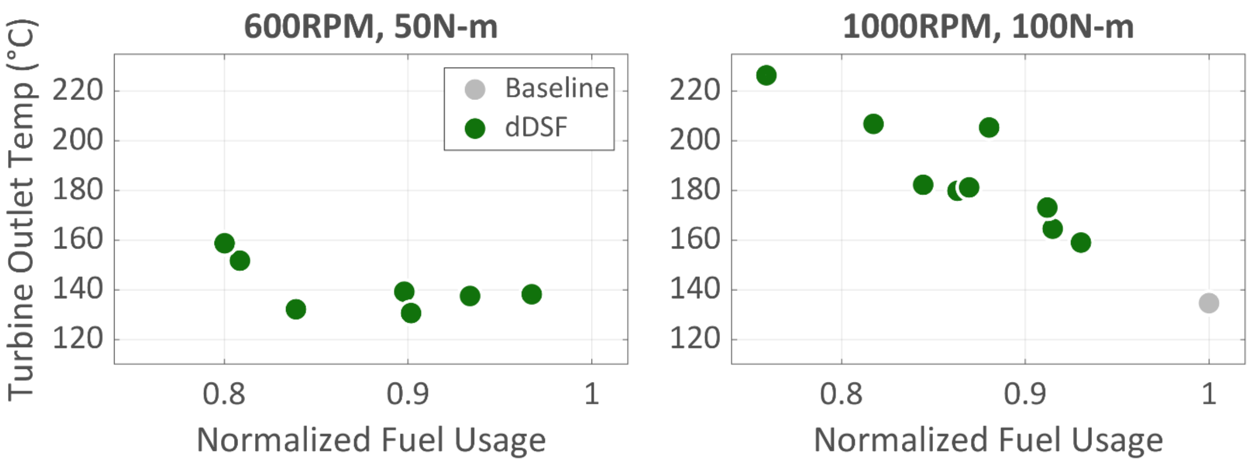

Figure 6: Turbine Outlet Temperature as a function of Fuel Usage for Low and High Idle Engine Speeds

Figure 7 shows the impact on key other emissions as firing fraction is reduced. The calibration was developed to optimize smoke and hydrocarbons at low firing densities, at the expense of increased NO_x emissions. This intentional tradeoff was made to address the calibration goals for relevant applications. When a different tradeoff of fuel consumption, temperature, NO_x, THC, and particulates is desired, different firing densities, EGR rates, and fueling strategies would be used.

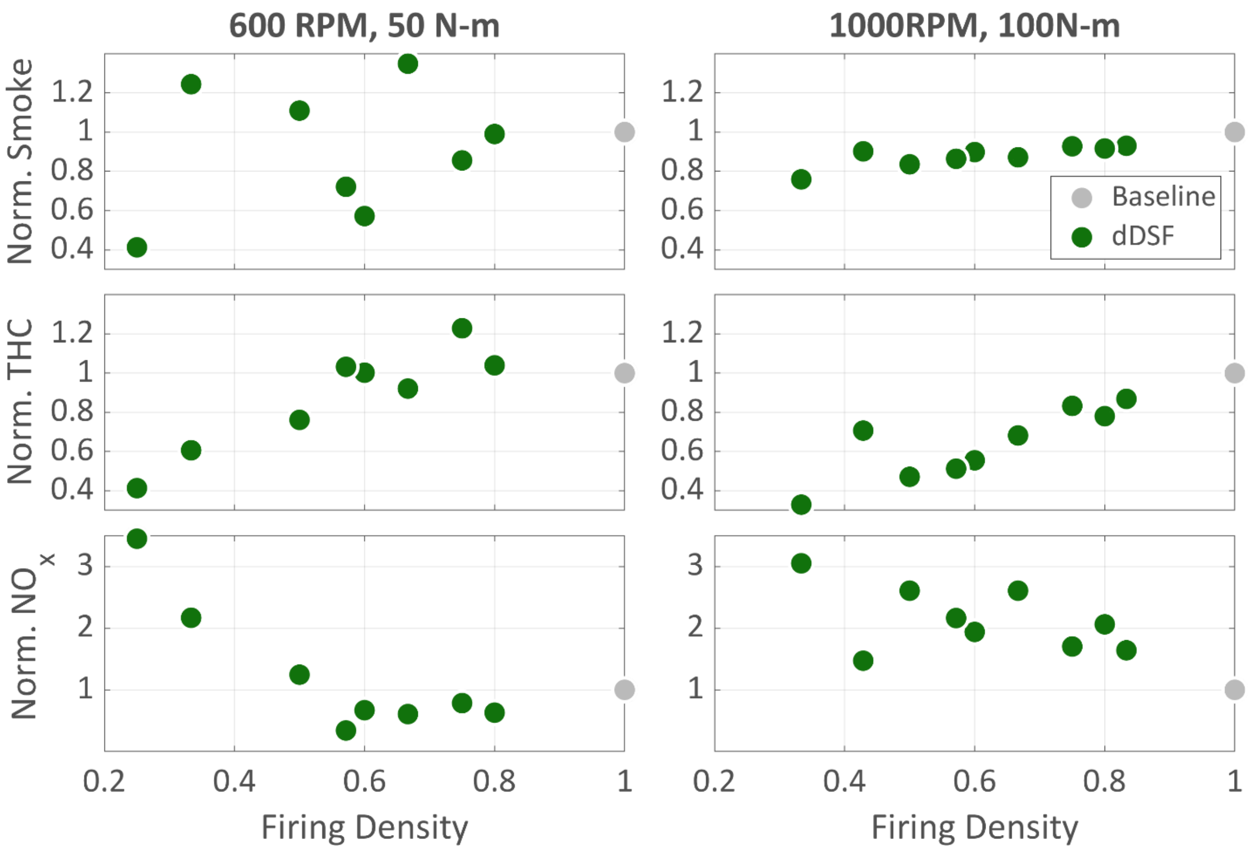

Figure 7: Key Engine-out Pollutant Trends as a Function of Firing Density for Low and High Idle Engine Speeds

NVH and Vehicle Response

To evaluate the impact of dynamic skip fire on vehicle drivability, Tula and Cummins conducted vehicle experiments on a Freightliner Cascadia line haul truck with a 12 speed automated manual 'Endurant' transmission. The prototype controller was outfitted with software created through collaboration between Cummins and Tula.

Firing sequences were evaluated to determine the torque levels at which operation did not adversely affect driver comfort or engine durability requirements. The maximum torque permitted at 1000 RPM is shown in figure 8. At firing densities above 0.5, torque levels of up to 380 N-m are permitted. At lower firing densities, the acceptable maximum torque is reduced.

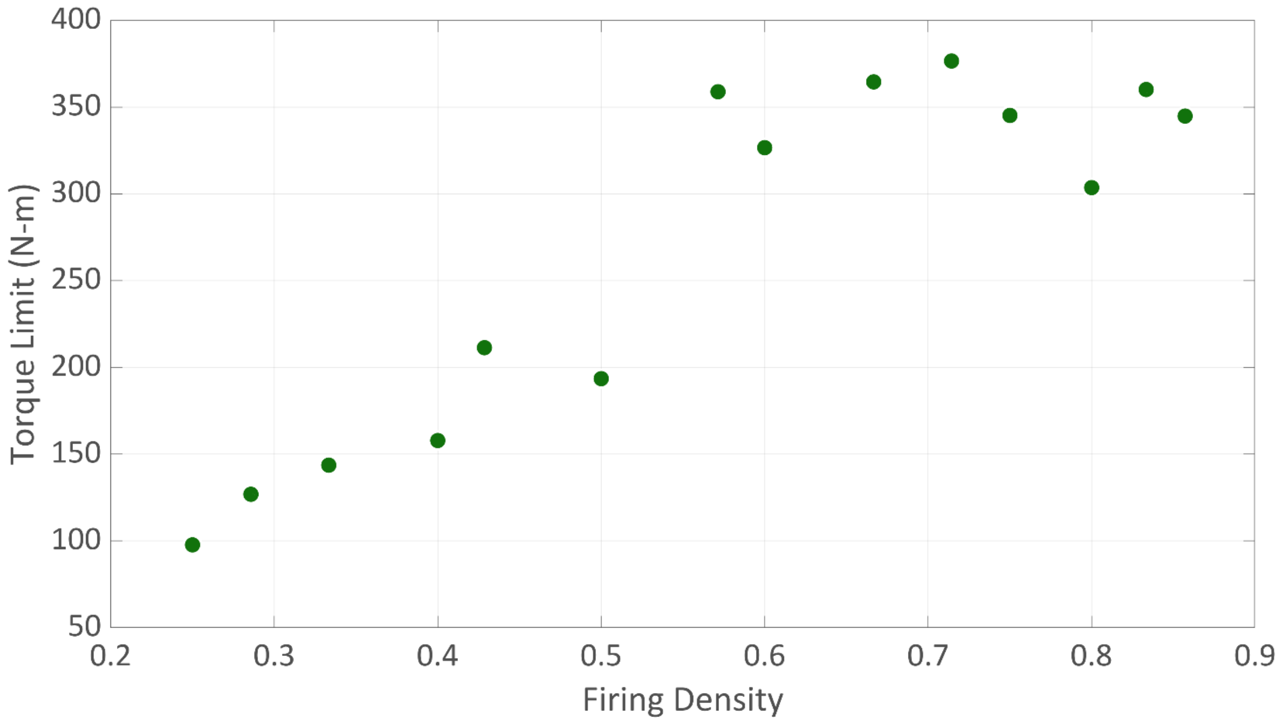

Figure 8: Maximum Torque Acceptable at a variety of steady-state firing densities

In contrast to figure 8, which shows the maximum torque possible for each firing density, figure 9 shows the calibration as implemented at a variety of brake torque levels. At low torque levels, firing density is low and temperatures are increased by 75ºC to 100ºC. Although aftertreatment temperature management strategy is complex, the flexibility offered by dDSF makes maintaining conversion efficiency far easier.

As an arbitrary yet relevant demonstration of that, figure 9 includes a graph of available enthalpy relative to a 200ºC condition. In baseline operation, all points lower than 430N-m effectively begin to cool the aftertreatment system. In contrast, dDSF maintains or improves enthalpy delivered to the aftertreatment system throughout the range of operation. This impact will vary as the aftertreatment control temperature changes relative to the 200ºC example used here.

Furthermore, figure 9 shows the dramatic improvement possible during deceleration, comparing conventional Deceleration Fuel Cut-Off (DFCO) with Deceleration Cylinder Cut-Off (DCCO). In DFCO, all cylinders are unfueled, resulting in airflow cooling the catalyst at a rate of approximately 6 kilowatts. In contrast, DCCO shuts off a majority of cylinder events, flowing only enough air to keep the turbine speed above thresholds required for durability. As such, the cooling power delivered to the turbine is reduced by approximately 50% to only 3 kilowatts.

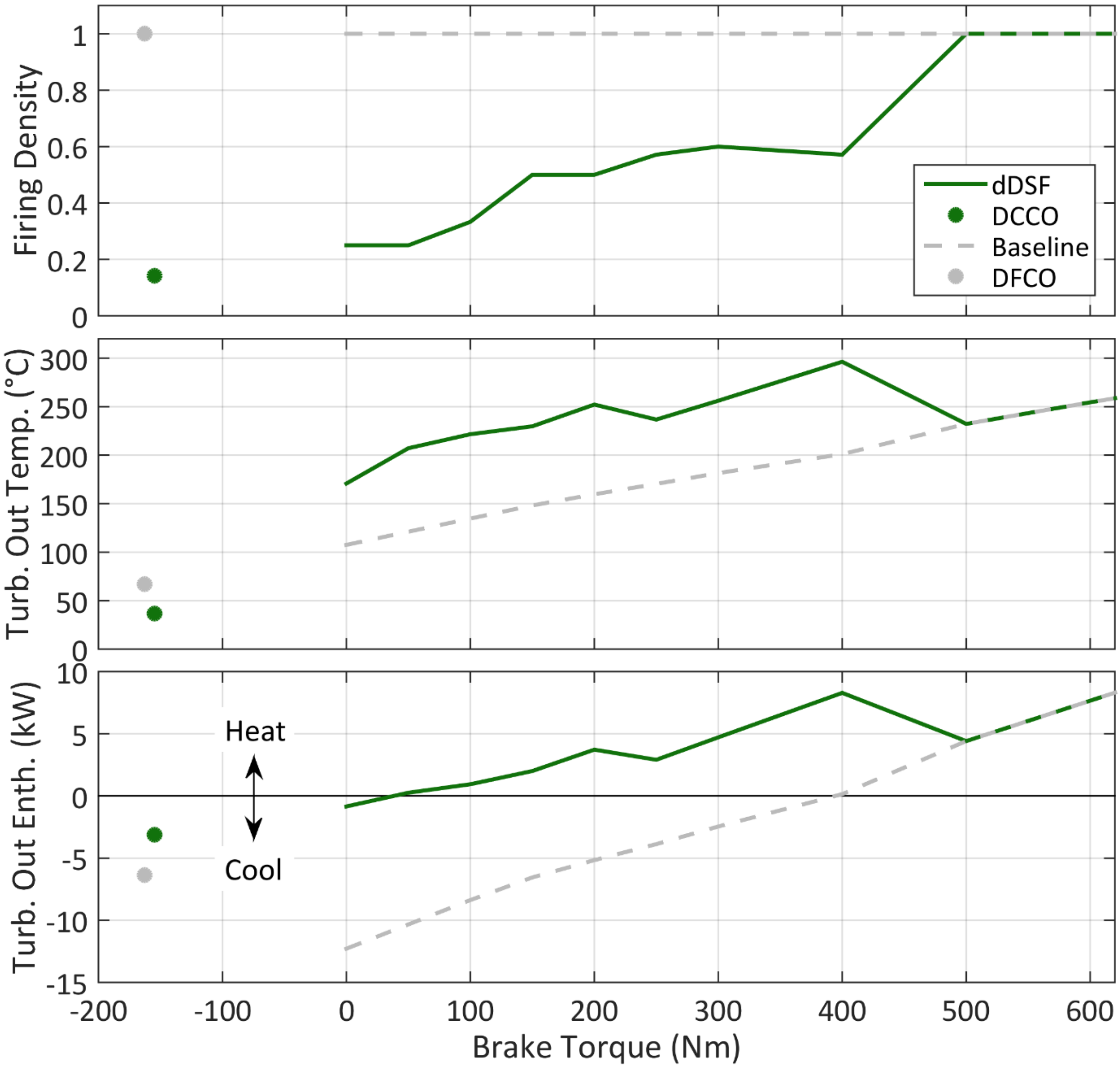

Figure 9: Suggested Calibration and resulting Turbine Outlet Temperature, 1000 RPM

While figure 8 showed the maximum torque acceptable at 1000 RPM, figure 10 shows the calibration as implemented in-vehicle, comparing dDSF to baseline operation. To provide small, positive brake torque levels, low firing densities are recommended. In this calibration, firing densities between 0.25 and 0.30 were used below 100 N-m. At those conditions, turbine outlet temperatures show remarkably increased exhaust gas temperatures. In these conditions, temperature gains of up to 100ºC are common.

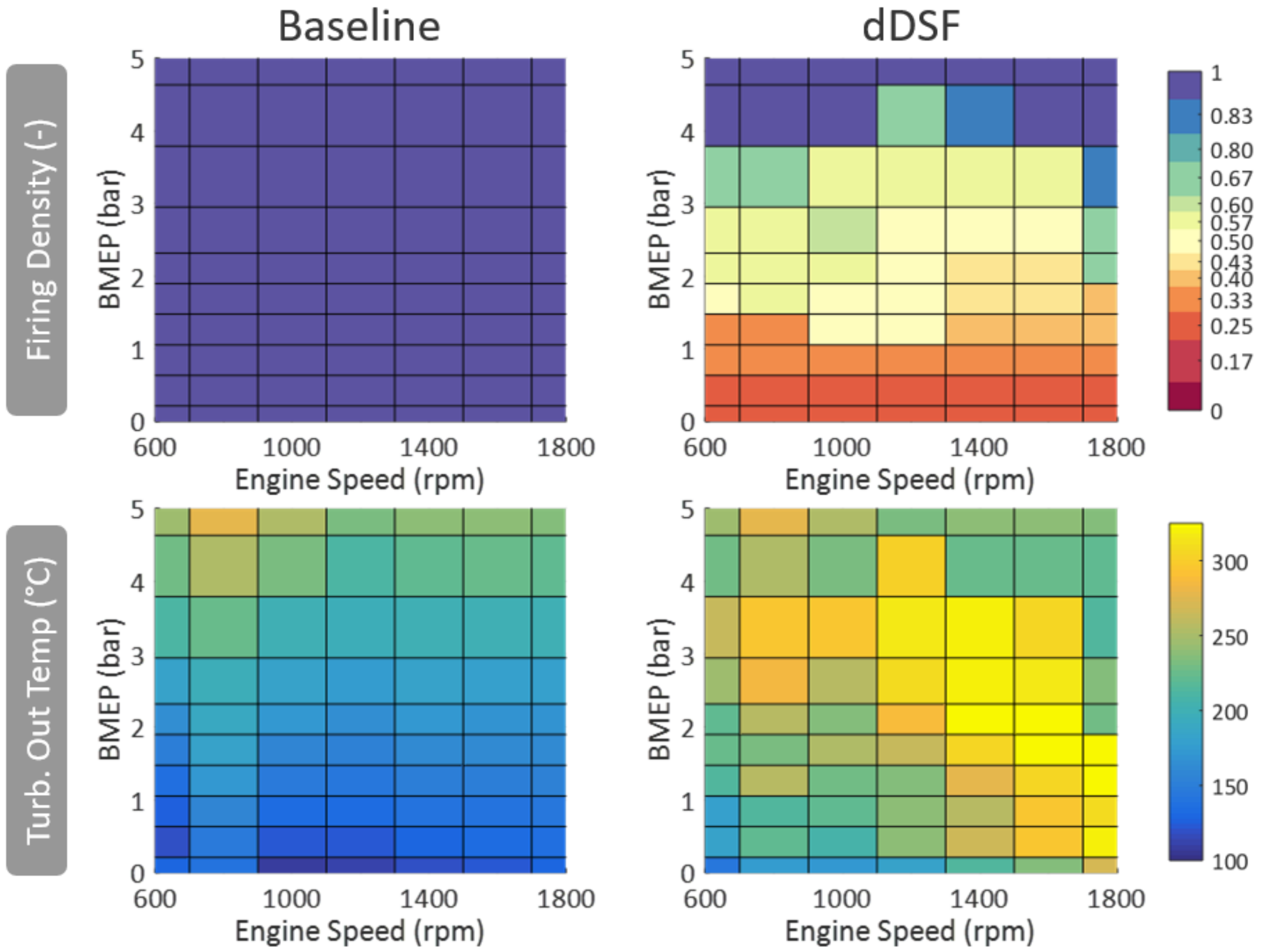

Figure 10: Comparison of baseline engine operation dDSF

Test Cycle Results

In order to determine the improvement in NO_x and CO_2 emissions control for the US HD FTP and the new low load cycle LLC #7 proposed by California Air Resources Board, transient simulations were conducted. Engine out conditions were defined by engine dynamometer experiments and conventional thermal management strategies for the initial warm-up of the catalyst system. The transient simulations were a first step to evaluate the advantages of dDSF for operation over test cycles and in-use duty cycles. Evaluations were performed to demonstrate the benefit of dDSF over the baseline 2017 X15 system, with and without increased conventional thermal management (ICTM). Work under the collaboration will continue to evaluate and optimize dDSF performance over test and real world cycles on both the transient dynamometer and in vehicle.

In addition to the dDSF calibration and increased conventional thermal management, simulations were carried out with Cummins proprietary after-treatment models that were developed to model performance of the catalyst system at full useful life (435k miles for CARB and EPA) including both thermal and chemical degradation effects. The California Air Resources Board is expected to propose additional increases in useful life for 2027 and 2031 in their Omnibus Rule making. Those increases in useful life were not included in the scope of this evaluation.

Figure 11 shows the results of the simulation work using the initial dDSF calibration to mitigate NVH for vehicle testing. Results show a NO_x reduction of 45% on the HD FTP cycle and 66% on the proposed LLC #7.

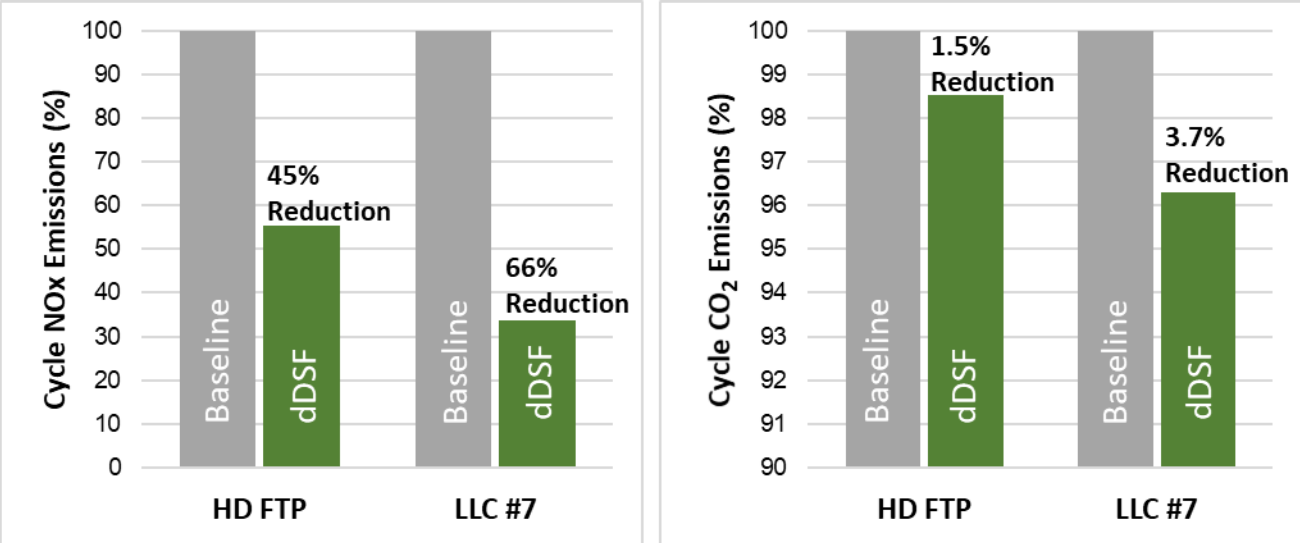

Figure 11: Comparison of Baseline and dDSF CO_2 and NO_X on HD FTP cycle and LLC

In figure 12, a direct comparison is made between dDSF, ICTM, and the combination of those technologies. The tradefoff between NO_x and fuel consumption is shown. In comparison with conventional ICTM strategies, dDSF simulation showed similar NO_x performance on the HD FTP, while improving fuel consumption by 1.5% over the baseline system, and 3-4% over a system with similar NO_x reduction using conventional thermal management strategies. For the LLC, NO_x reductions of 66% are achieved relative to the baseline system with a 4% CO2 reduction. When compared to NO_x reductions obtained through ICTM, the simulations showed that dDSF improves NO_x by over 50% at a fuel consumption improvement of 6-9%.

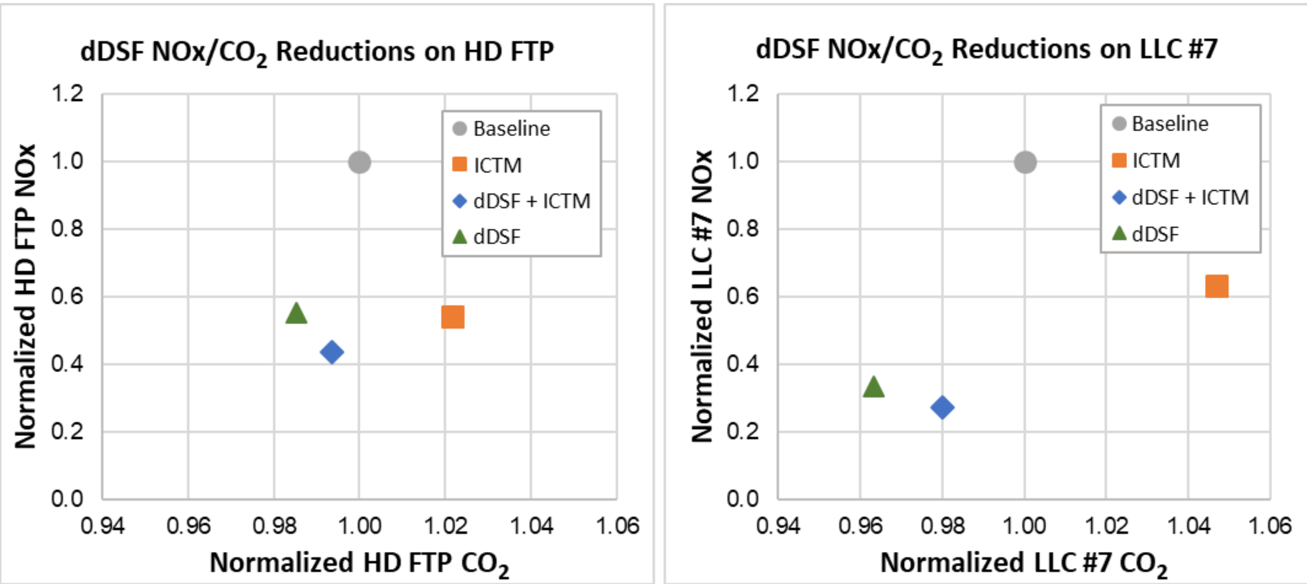

Figure 12: Tradeoff of Baseline and dDSF CO_2 and NO_X on HD FTP cycle and LLC

Furthermore, full engine optimization strategies have not yet been completely exhausted, and further improvements should be realized in the near future.

Details of the currently recommended strategy for dDSF+ICTM are shown on the HD FTP and LLC in figures 13 and 14, respectively. On the HD FTP, the engine is operated at less than all cylinders approximately 55% of the time. Predicted aftertreatment temperatures are improved throughout the drive cycle, including an increase of 80ºC during the critical first 200 seconds of the drive cycle. Accumulated NO_x is modeled to be improved by about 55%.

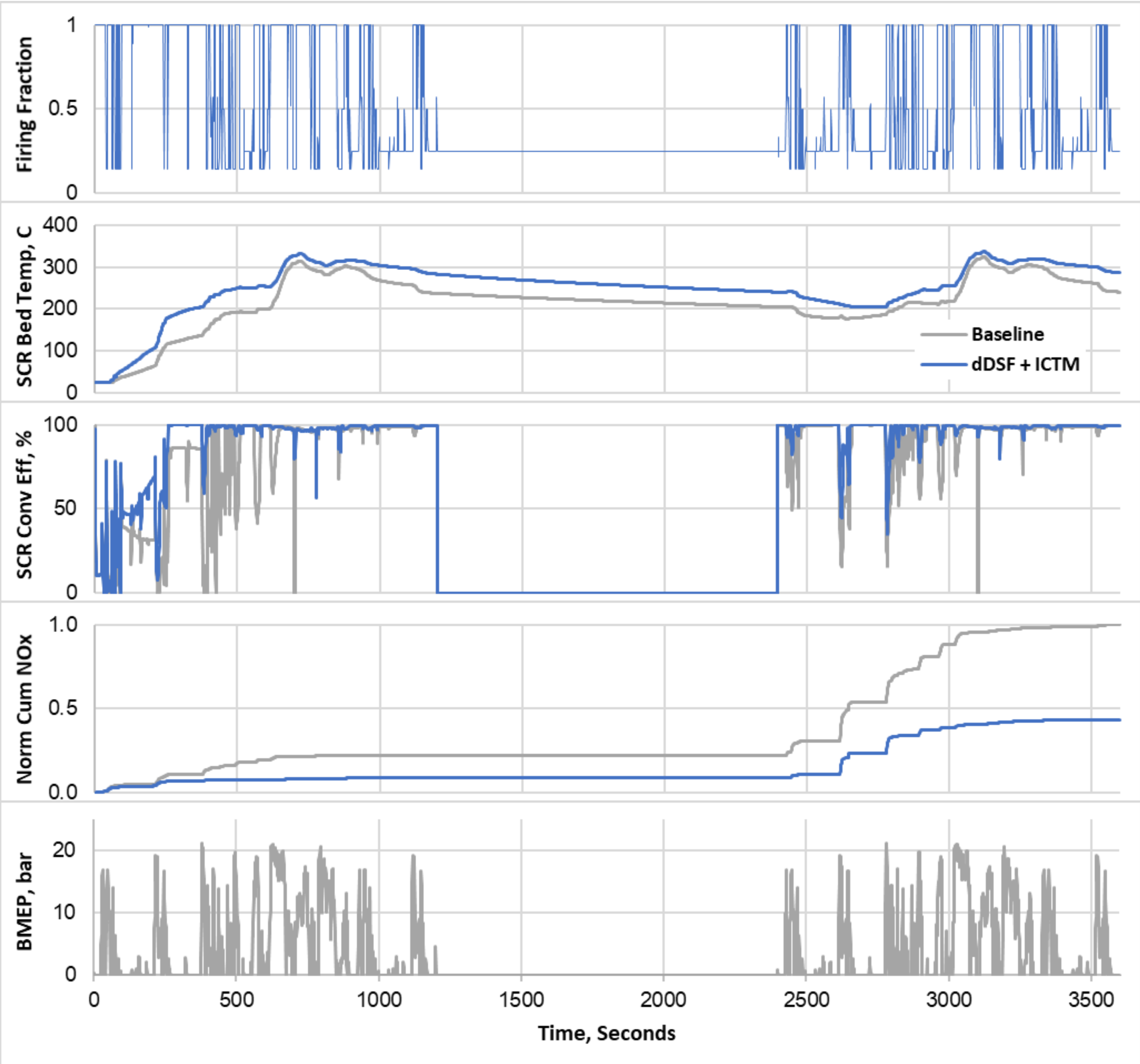

Figure 13: dDSF operation on HD FTP cycle

Figure 14 shows the details of simulated X15 dDSF operation on the LLC#7. Firing densities are below 100% for approximately 80% of the drive cycle. Predicted SCR temperatures are generally improved by 50-75ºC and accumulated NO_x is improved by 70%.

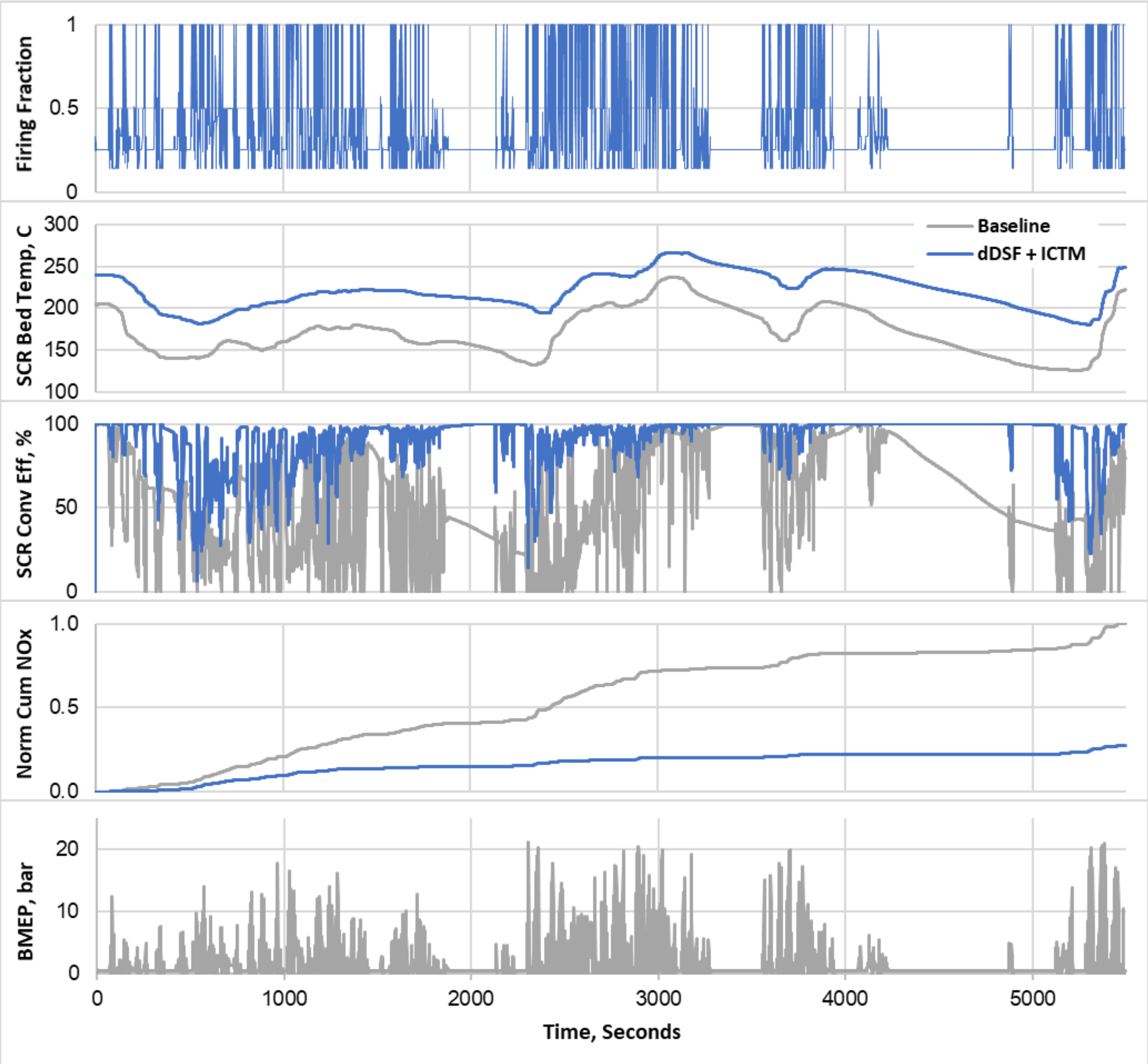

Figure 14: dDSF operation on proposed LLC#7

Conclusions

The collaboration between Cummins and Tula in implementing dDSF has demonstrated large improvements in emissions, while simultaneously reducing fuel consumed, at some steady-state conditions. Compared to ICTM strategies, dDSF was simulated to improve fuel consumption by 3-4% on the HD FTP cycle. Compared to ICTM, dDSF was simulated to improve fuel consumption by 6-9% on the LLC cycle, while simultaneously cutting the NO_x emitted by over 50%.

In addition, dDSF can be combined with ICTM. The combined effects predicted a 55% reduction in NO_x emissions and a 1% improvement in CO_2 over the 2017 baseline X15 system. On the proposed LLC #7, the simulated combined effects resulted in a 70% reduction in NO_x emissions and a 2% reduction in CO_2.

The technology, expanded from prior use in production gasoline passenger vehicles, is now being demonstrated in an industry leading engine and vehicle. Cummins, Inc. and Tula Technology, Inc. are continuing to develop this technology with a full optimization of the system and vehicle demonstration which will be shared with the industry later in 2020. This final demonstration is expected to establish the efficacy of the application of dDSF for commercial vehicle applications. Further work is required to determine whether that the technology can meet durability, reliability and cost targets for future products.

References

[1] Younkins, M., Fuerst, J., Carlson, S., Kirwan, J., et al., "Dynamic Skip Fire: The Ultimate Cylinder Deactivation Strategy," 38th International Vienna Motor Symposium, Vienna 2017.

[2] Younkins, M., Ortiz-Soto, E., Wilcutts, M., Fuerst, J., Rayl, A., "Dynamic Skip Fire: New Technologies for Innovative Propulsion Systems," 39th International Vienna Motor Symposium, Vienna 2018.

[3] Gosala, D., Allen, C., Ramesh, A., et al., "Cylinder Deactivation During Dynamic Diesel Engine Operation," International Journal of Engine Research 2017, Vol. 18(10) 991–1004

[4] Ramesh, A., Gosala, D., Allen, C., Joshi, M. et al., "Cylinder Deactivation for Increased Engine Efficiency and Aftertreatment Thermal Management in Diesel Engines," SAE Technical Paper 2018-01-0384, 2018

[5] Scassa, M., George, S., Nencioni, M., Chen, S. et al., "Dynamic Skip Fire Applied to a Diesel Engine for Improved Fuel Consumption and Emissions," SAE Technical Paper 2019-01-0549, 2019, https://doi.org/10.4271/2019-01-0549.

[6] Ortiz-Soto, E., Chen, K., Younkins, M., Scassa, M., Nencioni, M., et al., "Advances in Dynamic Skip Fire: mDSF and dDSF," 28th Aachen Colloquium Automobile and Engine Technology, Aachen 2019.

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