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Meeting Future NO_X Emissions Over Various Cycles Using a Fuel Burner and Conventional Aftertreatment System

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Abstract

The commercial vehicle industry continues to move in the direction of improving brake thermal efficiency while meeting more stringent diesel engine emission requirements. This study focused on demonstrating future emissions by using an exhaust burner upstream of a conventional aftertreatment system. This work highlights system results over the low load cycle (LLC) and many other pertinent cycles (Beverage Cycle, and Stay Hot Cycle, New York Bus Cycle). These efforts complement previous works showing system performance over the Heavy-Duty FTP and World Harmonized Transient Cycle (WHTC). The exhaust burner is used to raise and maintain the Selective Catalytic Reduction (SCR) catalyst at its optimal temperature over these cycles for efficient NO_X reduction. This work showed that tailpipe NO_X is significantly improved over these cycles with the exhaust burner. In certain cases, the improvements resulted in tailpipe NO_X values well below the adopted 2027 LLC NO_X standard of 0.05 g/hp-hr, providing significant margin. In fact, near zero NO_X was measured on some of these cycles, which goes beyond future regulation requirements. However, burner operation on the tested cycles also resulted in a CO_2 increase, indicating that a different burner calibration strategy, or possibly an additional technology, will be needed to achieve lower CO_2 emissions.

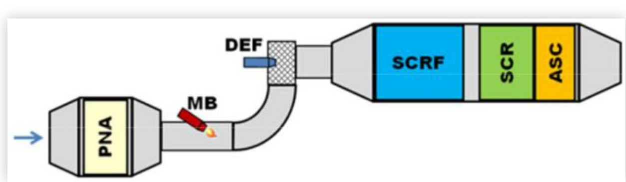
Introduction

The California Air Resources Board (CARB) adopted the Low NO_X Omnibus regulation in 2020 to lower diesel exhaust emissions [1]. The adopted regulation covers several critical areas like reduced NO_X emission standards, durability requirements, and updates to engine family certification procedures [1, 2]. The United States Environmental Protection Agency (EPA) also introduced a notice of proposed rulemaking, which is aligned with CARB's regulatory updates [3, 4]. As a result, the commercial vehicle industry has already started introducing potential pathways and strategies for complying with low NO_X standards. Examples of this include cylinder deactivation, close coupled SCR, electric heaters and fuel burners as means to lower emissions [5-9]. Despite the myriad of options and technology combinations available, there are still questions regarding the impact of CO_2 and NO_X utilizing novel thermal management technologies.

Burner based technologies have had a presence in the commercial vehicle industry as diesel particulate filter regeneration enablers [10]. In recent years, burner systems have become a potential thermal management technology designed to enable rapid aftertreatment system warm-up during cold starts and to sustain ideal catalyst temperatures. For engines that inherently generate low temperature exhaust, the burner can be an attractive option to achieve future NO_X compliance. In the CARB stage 1 program, for example, the engine platform's exhaust conditions required the use of a passive NO_X adsorber (PNA) and mini burner (MB) [11]. During cold starts, the PNA stored NO_X at low temperatures while the burner heated the SCR catalysts. The system, which is shown in Figure 1, was configured such that the SCR catalysts achieved operating temperature as the PNA was releasing stored NO_X.

The following work investigates the impact of a burner-based technology utilized for thermal management. Test articles operated in this study include a Cummins X15 engine, a conventional aftertreatment system with advanced catalyst

FIGURE 1 Stage 1 low NOX aftertreatment system [10].



formulations targeted for a representative system in 2022, and a burner system. This system represents the least complex technology package proposed for a future low-NO_X standard, and potentially enables a current production aftertreatment system to be upgraded with minimal impact to packaging on the vehicle. This same system was utilized to obtain very encouraging NO_X and CO_2 results on the FTP and WHTC cycles [9]; some details from this work are included in the Appendix.

In addition to the test article results, reported results from a separate technology approach will be introduced to provide a comparison between low NO_X viable solutions. The referenced approach utilized a light-off SCR (LO-SCR) and cylinder deactivation (CDA) package [12-16]. The discussion will focus on the burner solution's results over low load cycles such as the LLC and Beverage cycle. The ability for the burner to keep the SCR hot is shown next during the stay hot test. Then, results for two other bus cycles and NYBC, are provided. A CO_2 and NO_X tradeoff analysis will also be provided to understand how separate technology packages compare.

Engine Platforms

Test Engine

The test engine platform utilized was a production MY2020 Cummins X15 certified to comply with 2010 U.S. on-road emission standards. Prior to the start of testing, the engine control unit (ECU) calibration was re-configured with a 500 hp production calibration utilized in the CARB Stage 3 on-road baseline testing. The ECU re-configuration was completed to enable direct test bed comparisons to the stage 3 low NO_X program. It is also worth noting that alternative calibrations were considered but did not yield a sufficient CO_2 reduction to offset the engine out NO_X emissions increase. Beyond the calibration change, the engine retained the production air handling system, EGR system, internal components, and fuel system. It should be emphasized that this engine was not up-fitted with CDA. The engine is shown in Figure 2 and the specifications are listed in Table 1.

FIGURE 2 Cummins X15 engine platform installed in test cell.

TABLE 1 Cummins X15 engine parameters.

Parameter	Value
Configuration	Inline 6
Bore x Stroke	137 x 169 mm
Displacement	15.0 L
Rated Power	373 kW (500 hp)
Rated Speed	1,800 RPM
Peak Torque	2,500 Nm
Peak Torque Speed	1,000 RPM

Test Cell

Emission results discussed in this work were generated in a Code of Federal Regulations Part 1065 compliant engine dynamometer test cell utilizing raw exhaust measurements. Relevant measurement equipment included the following:

- A raw Horiba MEXA 7000 series for the tailpipe emissions sampling
- One FTIR for engine out (i.e., NO_X) or tailpipe emission measurements (i.e., NH_3 and N_2O) to periodically check for NH_3 slip.
- A "day" tank-based test cell fuel system configured to measure total fuel consumption
- A Coriolis type fuel flow meter directly measuring the burner fuel consumption

Aftertreatment performance was evaluated by testing transient cycles, which included the Heavy-Duty Federal Test Procedure (HD-FTP), World Harmonized Transient Cycle (WHTC), Low Load Cycle (LLC), and several field cycles. For the purposes of this work, the LLC and field cycles will be the primary discussion topic.

Because the engine was not turning an alternator to power burner operation, parasitic loading needed to be simulated in real time through additional dynamometer loading. This was achieved by outfitting the burner system with current and voltage measurements.

The measurements were utilized to quantify the burner power requirement and its equivalent parasitic load. The parasitic load was then applied to the target cycle torque in real time similar to previous works [8]. This same parasitic loading included an alternator efficiency of 80%.

Aftertreatment System

Since the objective was focused on evaluating a thermal management approach designed for future regulatory compliance, a burner was paired to an advanced aftertreatment system. This provided a burner-based candidate solution designed to meet future NO_X compliance standards starting in 2024 and onward. Figure 3, which depicts the aftertreatment architecture, was a conventional architecture comprised of a burner, DOC, DPF, compact mixer, SCR, and ASC. Compared to catalysts designed to meet the 2010 on-road emissions standards, the test system includes components with improved formulations and sizing selections consistent with catalysts expected in 2022. For example, the system had ~25% more SCR volume compared to optimized catalysts meeting the 0.2 g/hp-hr tailpipe NO_X standard. Other elements, such as the feedback devices, the inlet cone diffuser, the DEF delivery system, and the DEF mixer share the same specification or design elements used on MY2020 production systems. Distance between the turbine outlet and the aftertreatment inlet was maintained at 4' for the entirety of this campaign. As a final note, the advanced aftertreatment system discussed herein was developed for low NO_X emission studies in 2019.

Figure 3 provides an aftertreatment schematic of the system tested, Figure 4 provides the aftertreatment system installation downstream of the burner and Table 2 provides the catalyst specifications. Engine exhaust enters the burner assembly followed by the DOC-DPF-SCR-ASC system. The burner had a maximum instantaneous heating potential of 53 kW which could be trimmed down for lower requirements. The results discussed in this paper were achieved without any insulation applied to the exhaust system. Favorable results were found by adding insulation to the exhaust system and the comparison is provided in a previous study [9].

The burner installed upstream of the aftertreatment system was comprised of air delivery, ignition, and fuel systems. As previously mentioned, the electrical system was instrumented to calculate a parasitic load during cycle operation. The air delivery system utilized an Eaton roots blower coupled to a commercially available 24-volt motor. Future designs will have both 12- and 24-volt motors depending on the application need. The ignition and fuel systems included mostly automotive grade components and were designed to leverage existing commercial vehicle systems (i.e., 12V electrical for the engine fuel supply system). Feedback devices such as exhaust temperature sensors and flow meters were

FIGURE 3 Test aftertreatment system comprised of a burner, DOC, DPF, mixer, SCR, and ASC.

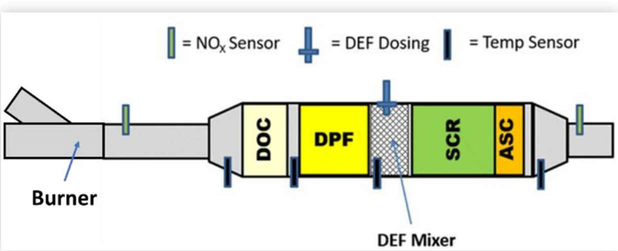


FIGURE 4 Aftertreatment installation.

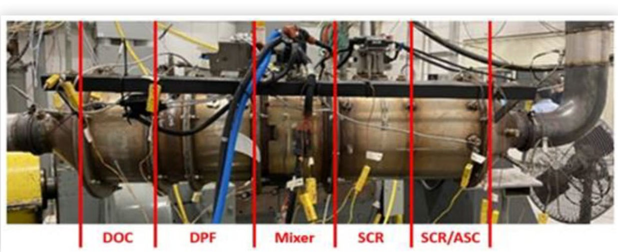
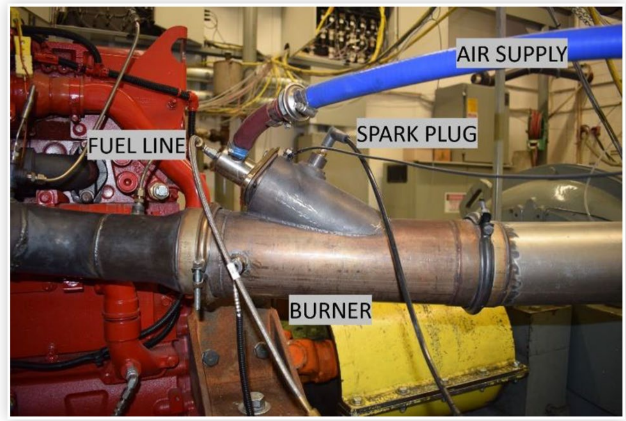


TABLE 2 Advanced system catalyst specifications.

Component	D x L	CPSI	Volume
DOC	13" x 5"	400	11 L
DPF	13" x 7"	300	15 L
SCR	13" x 6"	600	13 L
SCR-ASC	13" x 6"	600	13 L

FIGURE 5 Exhaust burner.



also installed to control burner conditions. The installed burner is shown in Figure 5 along with labels indicating the different supply lines and spark plug (igniter) locations.

For the purpose of protecting the DOC from excessive heat, the burner included a closed-loop control system to an exhaust temperature sensor located in the inlet cone of the aftertreatment system. The setpoint temperature for this control was 525° C for pre-heating and when the engine was running. In addition, the burner controls made use of an on/off switch associated with an exhaust temperature sensor located at the DPF outlet. This switch, which caused the burner to turn off when its threshold was reached, is important for managing the trade-off between NO_X and CO_2 emissions. This threshold was either single-valued (e.g., 200° C) or "2-tier" (e.g., an initial upper value of 300° C, followed by a lower value of 200° C); the latter was found in a previous study to be helpful for achieving very low emissions over the FTP cycle [9]. This "2-tier" strategy features an initial upper threshold value that can achieve the rapid warm-up objective, and a lower threshold that can achieve the temperature maintenance objective. The majority of the test results used an upper SCR threshold of 300° C and the lower threshold of 200° C. This strategy worked well for rapid heat-up of the AT system which was then maintained at the lower threshold once the DPF was heated up.

The aftertreatment system was initially evaluated in a Degreened state to quantify tailpipe NO_X emissions. After completing the testing, it was exposed to hydrothermal aging utilizing an accelerated aging protocol on a burner based aging platform. The protocol targeted the equivalent amount of heat loading for a full useful life (FUL) system i.e., 435,000 miles or 9,800 hours of service accumulation time, similar to previous works [5, 7-9]. This has been commonly referred to as "Development Aged" end of life catalysts. The aging conditions included one steady state exhaust and high temperature target for a total of 100 hours. Sulfur exposure and lubricant derived poisoning, which are the primary chemical aging deterioration mechanisms, were not included in the aging protocol.

A model-based controller developed by Southwest Research Institute [6, 7, 11] was utilized in these tests. It was tuned for the best performing aftertreatment system and compared to the production setup. In general, slightly less DEF was used to maximize NO_X reduction and minimize NH_3 slip. The model-based controller utilized the same fundamental framework as reported in other low NO_X demonstrations [6, 11]. It was also updated to interface with the burner controller so different thermal management strategies could be executed. For this study, the production controller and model-based options were found to yield similar NO_X performance. However, emissions data revealed that the production controller led to tailpipe NH_3 emissions. Therefore, the model-based approach was used to predict the SCR NH_3 loading more accurately and to mitigate NH_3 slip. The controller implementation also reflects a potential controls approach to manage excessive N_2O emissions resulting from NH_3 reactions across the ASC.

Results

This section is broken into three parts. First, the results of the fuel burner with the conventional AT system will be provided over the Beverage and LLC cycles. The second section will show a comparison of the burner/conventional AT system versus a system to has been shown to meet 2027 over both the LLC and Stay Hot cycles. The last section will show a comparison of the burner/conventional AT system verses another system with and without CDA over the NYBC cycle.

Test Results: Beverage and LLC Cycles

The Beverage and LLC are shown in this section for improving SCR temperatures with the burner to reduce NO_X emissions. The Beverage cycle was used for strategy development as it one the lowest load portion of the LLC and is only 800 seconds long as opposed to the longer 1.5 hour LLC. This allowed for faster turn-around on controls variations. Once the optimal strategy was determined, this strategy was used on the LLC and later on the Stay Hot and NYBC cycles. It is important to note that CARB proposed NO_X standard for the LLC is 0.05 g/hp-hr while the beverage cycle, being a smaller portion of the LLC, doesn't have an explicit standard other than complying to in-use emission regulations. Since the controls optimization was completed first on the Beverage cycle, this is shown first followed by results of the LLC.

Beverage Cycle The Beverage cycle, which is part of the LLC subset, was generated by a delivery truck application. The cycle has an average load of 7.1% and is comprised of several transient ramps and idle sections lasting longer than 60 s. The cycle was executed by completing four (4) Beverage cycles (800 seconds each) back-to-back and then quantifying tailpipe emission values for the final two (2) cycles (i.e., 1600 seconds). The initial two (2) cycles are solely for aftertreatment conditioning (e.g., temperature and SCR NH_3 storage). The cycle speed and torque traces for the final two (2) Beverage cycles are illustrated in Figure 6.

Figure 7 shows the baseline and burner continuous data for SCR inlet temperature, NO_X reduction, and the estimated burner energy. It is worth noting that the burner was being operated utilizing the 2-tier 300 / 200° C strategy. With the burner configuration (FB+AT), the SCR inlet temperature is

FIGURE 6 Speed and torque for last two (2) Beverage cycles.

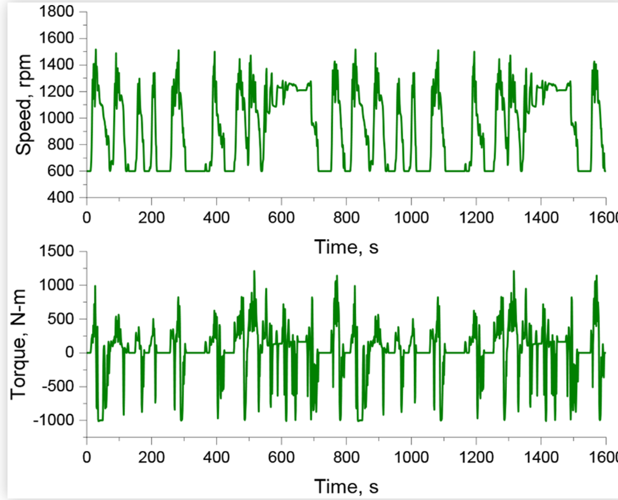
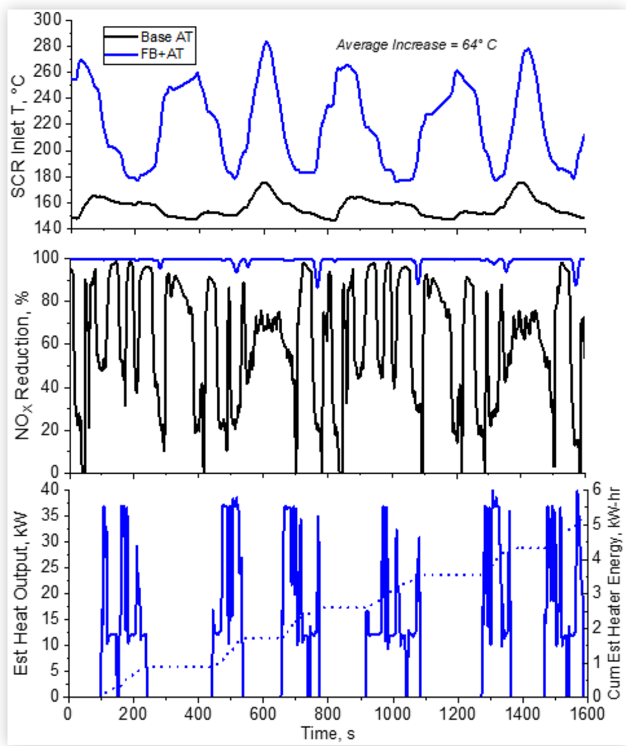


FIGURE 7 Comparison of the best burner test to base system over the Beverage cycle for SCR inlet temperature, NO_X reduction and estimated heat energy.



shown to have an average increase of 64° C. Compared the baseline result, which stayed below 170° C, the burner was able to maintain temperatures above 200° C. As can be shown in the NO_X reduction graph, this resulted in a significant tailpipe NO_X emissions improvement for the entire cycle, achieving nearly zero NO_X exiting the system. Figure 7 also highlights some of the challenges associated with placing the burner upstream of the DOC. When the SCR inlet temperature triggered the burner to turn "ON", it took anywhere from 50 s to 100 s before the SCR inlet temperature began increasing. This resulted in cyclical temperature behavior and the burner being "ON" for the time required to heat up the DOC and DPF. This cycle required a maximum heat of slightly below 40 kW while the accumulated energy over two cycles was approximately 5 kW-hr.

Figure 8 shows the cumulative CO_2 and tailpipe NO_X comparison for the baseline and the burner results. Since the burner experiment was able to maintain SCR operating temperatures, a 0.001 g/hp-hr NO_X result was measured for the burner experiment, or a 99.96% reduction compared to the baseline result (i.e., 2.147 g/hp-hr). This shows the potential that can be obtained for a near zero tailpipe NO_X configuration. However, the improvement in NO_X emissions also resulted in a 13.5% CO_2 increase over the baseline result. The burner allowed the engine to run slightly more efficiently, saving 0.4% CO_2.

In this study, several burner control strategies were considered to optimize the NO_X and CO_2 results for the FTP cycle. Some of these same strategies were then used in running the Beverage cycle; results are shown in Table 4. The strategies evaluated included a "2-tier" strategy (300 / 200° C) followed by some 1-tier approaches where the burner would be "ON" until the threshold SCR inlet temperature was met (e.g., 180° C and 190° C). Additional CO_2 emissions were observed with all of the strategies, with the 2-tier having the highest increase at 13.4%. The tailpipe NO_X results also highlight catalyst limitations within the strategy temperature thresholds. For example, configuring the threshold at 180° C showed an order of magnitude higher NO_X emissions compared to the threshold set at 190° C.

FIGURE 8 Comparison of best burner experiment to base system over the Beverage cycle for cumulative total NO_X and cumulative total CO_2.

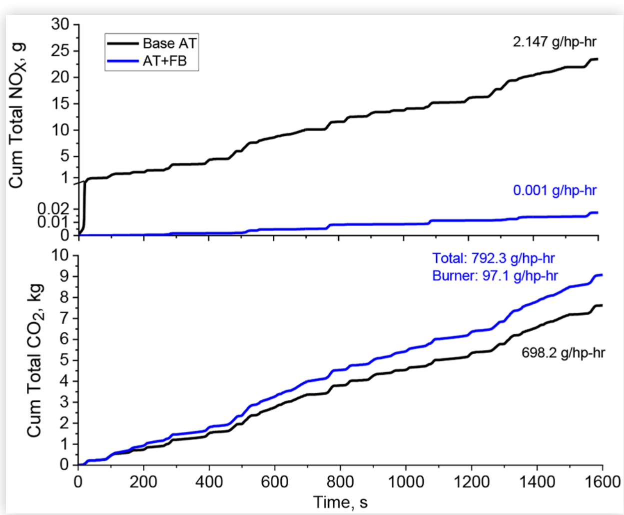
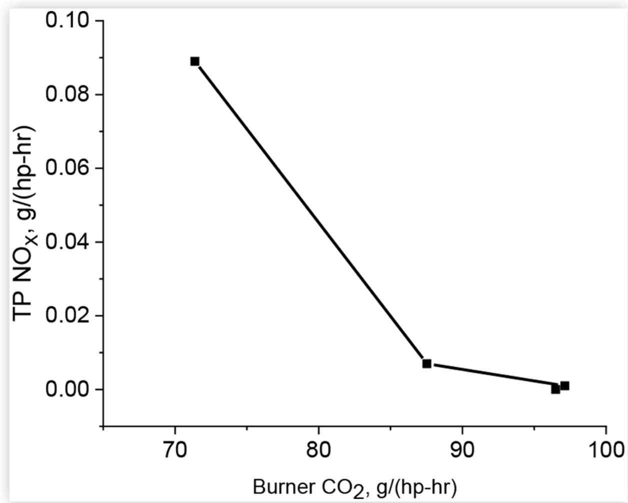


TABLE 4 Summarized results for multiple burner control strategies applied to the beverage cycle.

CONFIGURATION	EO BSNO$_X$ g/hp-hr	TP BSNO$_X$ g/hp-hr	TP BSCO$_2$ g/hp-hr	BURNER BSCO$_2$ g/hp-hr
Base AT	4.078	2.147	698.2	0
2-Tier: 300 / 200° C	5.993	0.001	792.3	97.1
1-Tier: 190° C	5.277	0.007	783.7	87.5
1-Tier: 180° C	5.255	0.089	763.2	71.4

FIGURE 9 NO_X and CO_2 trade-off for the Beverage cycle.

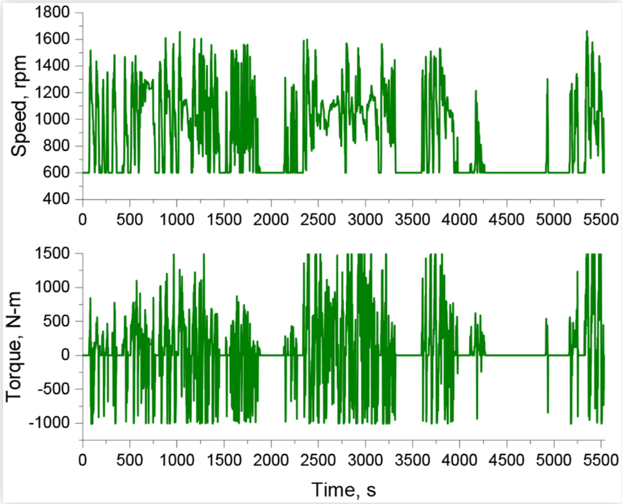


It should be mentioned that the CO_2 attributed to the burner in Table 4 is calculated based on the measured fuel amount. In addition, a close examination of the total CO_2 and burner CO_2 values indicates that the CO_2 produced by the engine (the difference between the two values) is reduced by <1% when the burner operates. This is due to the production engine, with its production calibration, spending less time in thermal management mode (with its higher CO_2 output) and less time in fuel economy mode [9].

Figure 9 shows that the NO_X-to-CO_2 trade-off was influenced strongly by the various burner on/off control thresholds considered. The lowest CO_2 result reflected a 9.3% increase over the baseline result and a 0.089 g/hp-hr for tailpipe NO_X (95% less than the baseline). Based on these preliminary results, an optimal threshold can be imagined. On the other hand, the trade-off is quite steep, suggesting that alternative control strategies should also be considered to ensure the best NO_X and CO_2 results.

Low Load Cycle The LLC is a pending new regulatory cycle that reflects real world operation which tends to be at a lower power than the US FTP. The cycle is over 5500 seconds long (~1.5 hours) and follows a hot FTP with a 20-minute soak in between. The cycle is shown in Figure 10. The high negative torque indicates full motoring at zero pedal.

FIGURE 10 LLC speed and load for the test engine.



The control strategy developed during the Beverage cycle using the 2-tier, 300 / 200° C approach is shown in Figure 11 for the LLC. The setpoint is initially 300° C and once that temperature is met, the setpoint drops to 200° C. In the top graph, the burner enables a 60° C average temperature increase. The SCR inlet temperature for the base configuration drops below 200° C for a considerable period, which accounts for the 77% NO_X reduction over the cycle, while the burner configuration maintains temperatures above 200° C. On the baseline system, the SCR is ineffective during this low temperature operation as shown in the middle graph for the instantaneous NO_X reduction. The burner enabled 99.9% NO_X reduction over this cycle due to the increased temperatures. The bottom graph shows the estimated burner heat pulses of up to 50 kW at discrete times along with the cumulative estimated heat energy (dotted line and right axis) of approximately 14.8 kW-hr over the LLC.

The cumulative total NO_X and CO_2 for this case is shown in Figure 12. Due to the lower exhaust temperatures, the base configuration has a 0.918 g/hp-hr TP NO_X cycle result, which is above the 2027 LLC requirement of 0.05 g/hp-hr, so new technology is required. The burner drops that TP NO_X value to 0.006 g/hp-hr (99.3% reduction), well below the 0.05 requirement. This shows the potential that can be obtained for a near zero tailpipe NO_X configuration. The base configuration $BSCO_2$ was 619 g/hp-hr while the$BSCO_2$ for the burner case was 675 g/hp-hr. The burner allowed the engine to run slightly more efficiently, saving 0.99% CO_2. The burner contributed 10.1% more CO_2 than the engine, resulting in the net 9.0% CO_2 increase that enabled the near zero NO_X tailpipe result.

The tabulated emissions results for the LLC are shown in Table 5. The base AT case is presented with three other burner cases. The first burner case is what was presented in the graphs above. The third case dropped the second control temperature to 190° C. In contrast to the Beverage cycle results, this lower threshold value did not result in lower CO_2 emissions. Once again, this brief survey of control strategies applied to this cycle was not intended to identify the best trade-off between NOx and CO_2; in fact, given that the TP NOx emissions are

FIGURE 11 Comparison of best burner run to base system over the LLC for SCR inlet temperature, NO_X reduction, and estimate heat energy.

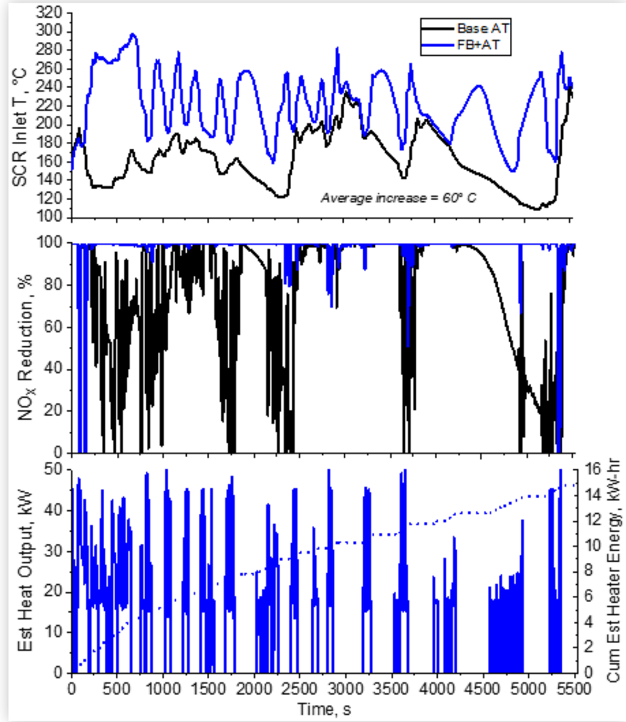


FIGURE 12 Comparison of best burner run to base system over the LLC for cumulative total NO_X and cumulative total CO_2.

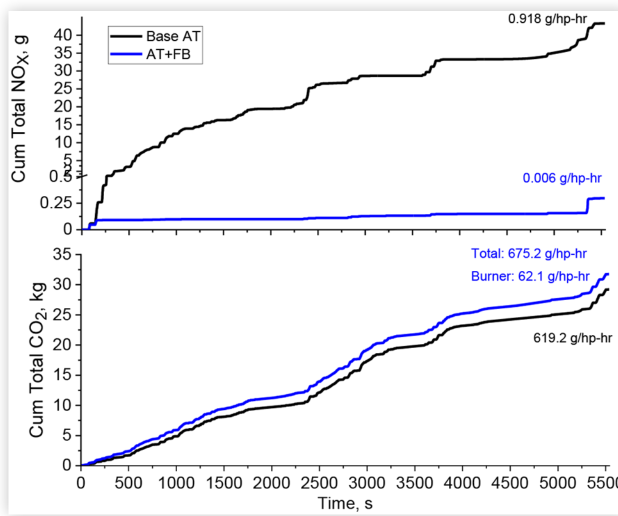


TABLE 5 LLC emissions results for base AT and two burner strategies.

Configuration	EO $BSNO_X$ g/hp-hr	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr	Burner $BSCO_2$ g/hp-hr
Base AT	4.002	0.918	619.2	0
2-Tier: 300 / 200° C	4.565	0.006	675.2	62.1
2-Tier: 300/ 190° C	4.617	0.008	685.4	67.6

near zero, it is easy to imagine that a better trade-off that still meets the LLC NOx limit can be realized through further controls development and system optimization.

As with the Beverage cycle above, a close examination of the total CO_2 and burner CO_2 values for the LLC indicates that the CO_2 produced by the engine (the difference between the two values) is reduced when the burner operates by ~1%. This indicates that the engine spends more time in fuel economy mode as a result of burner operation [9]. Given the lower threshold temperatures values of the 2-tier burner control considered here, it can be concluded that the after-treatment temperature associated with the engine's transition between the thermal management and fuel economy modes has a threshold value of ~200° C. If that threshold were to be reduced, the burner would consume even more fuel but a net reduction in total CO_2 emissions would be realized, because the engine would consume less fuel and, importantly, the burner converts fuel into exhaust heat much more efficiently than the engine [9].

Comparison with 2027 Compliant Setup

A comparison of the best burner setup with a conventional AT system is compared to the best CDA engine, LO-SCR and primary AT system in this section. This configuration used the CDA setup and aftertreatment setup from [5, 13] as shown in Figure 13.

LLC: Burner AT vs 2027 Compliant

Table 6 shows a comparison of the base aged primary system vs. the burner conventional system with 2-tier followed by the 2027 demonstration using CDA, a LO-SCR and primary AT system. The base system has higher NO_X emissions than proposed for 2027 on the LLC being less than 0.05 g/hp-hr. The burner 2-tier strategy achieves the LLC goal showing a 0.006 g/hp-hr NO_X. Likewise, the CDA+LO-SCR+ Primary also meets the LLC goal showing a 0.024 g/hp-hr. The burner system shows a slightly higher CO_2 by 8.4% over the CDA setup.

Stay Hot: Burner AT vs 2027 Compliant

The stay hot test consists of conditioning the engine and AT system at a given speed and load until temperatures are stabilized. Next, drop to idle for 40 minutes. Finally, return to same load previously, called return to service. Details of the test are shown in Figure 14.

A comparison of the SCR inlet temperature in the burner system to the inlet temperature to the LO-SCR inlet temperature of the 2027 compliant system is shown in Figure 15. The

FIGURE 13 LO-SCR followed by primary AT [13].

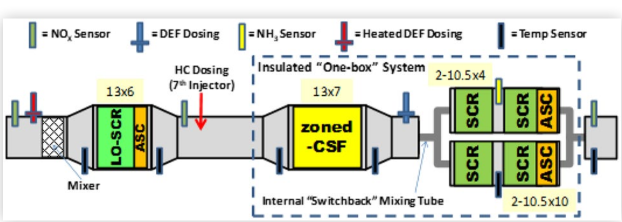


TABLE 6 LLC Comparison (2027 standard is sub 0.05 g/hp-hr).

CASE	$BSNO_X$ g/hp-hr	$BSCO_2$ g/hp-hr
Base Aged (Primay only)	0.918	511
Burner+Primary (2 tier)	0.006	675
CDA+LO-SCR+Primary	0.024	623

LO-SCR inlet from the base engine drops quickly to below 150° C. Adding CDA helps to extend the elevated temperature by approximately 10 minutes, while saving 11% CO_2 vs the non-CDA case, but this temperature also falls below 150° C. The burner system and the control strategy considered here allows the SCR inlet temperature to be controlled around the 200° C target, albeit with significant oscillation around that value.

The downstream thermal behavior produced by the burner under the conditions of this test (i.e., an extended period of engine idling) results from the simple on/off switch

FIGURE 14 Speed and torque for the stay hot test.

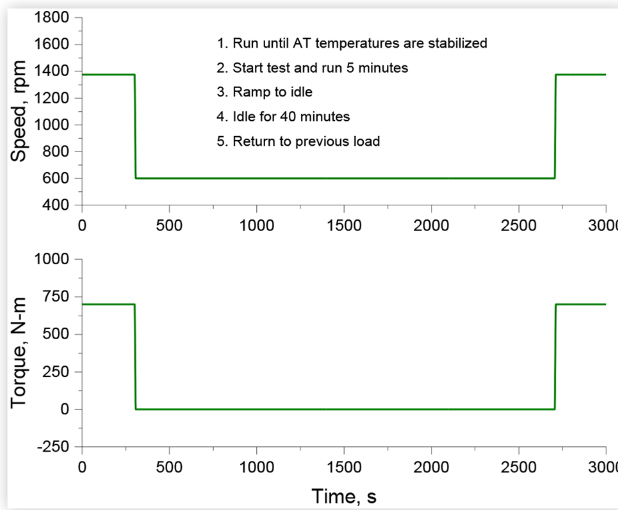
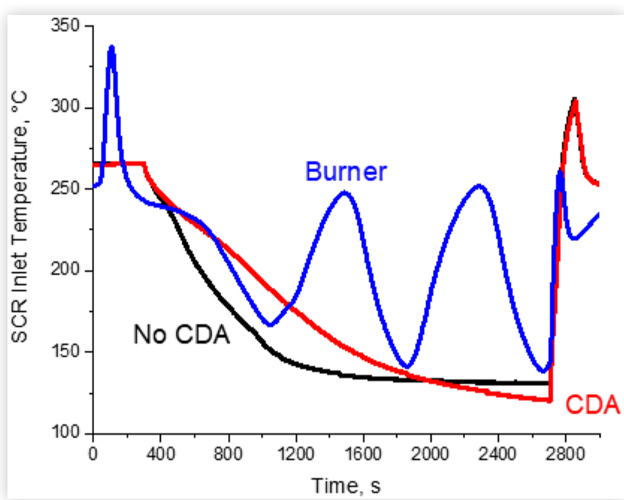


FIGURE 15 Comparison of burner run to system with and without CDA over the stay hot test for SCR inlet temperature.



associated with the DPF outlet temperature that was described as part of the burner controls above. After 200s into the test, the lower threshold of 200° C was applied to that switch; this resulted in an average temperature near that value. It is certainly possible to set that threshold to a lower value in order to achieve a lower average temperature in order to produce less CO_2. Burner control strategies that reduce the amplitude of the temperature oscillation may yield further reductions in CO_2 emissions.

The cumulative TP NO_X for these cases is shown in Figure 16. The SCR effectiveness for the baseline case drops after approximately 26 minutes of idle. CDA allows for the SCR to stay effective longer (well past 46 minutes) due to the temperature maintained by the LO-SCR catalyst with CDA. The burner maintains the SCR catalyst at very high activity throughout the cycle; in particular, the catalyst is still well prepared to convert the high NOx flux that challenges the system at the end of this cycle.

Table 7 shows the average temperatures and brake specific TP NO_X and CO_2. CDA alone helps to reduce TP NO_X by 95% while saving 10.5% CO_2. However, the LO-SCR inlet temperature is such that this is past around 1 hour of operation, so the engine and CDA system would have to trigger a heat-up mode for idling past an hour. Utilizing the burner, the NOx reduction is 99.9%. The CO_2 values cannot be absolutely compared because the data is from two different engines. The engine with the burner has approximately 5 points lower $BSCO_2$ that the Stage 3 engine.

FIGURE 16 Comparison of burner run to system with and without CDA over the stay hot test for cumulative TP NO_X.

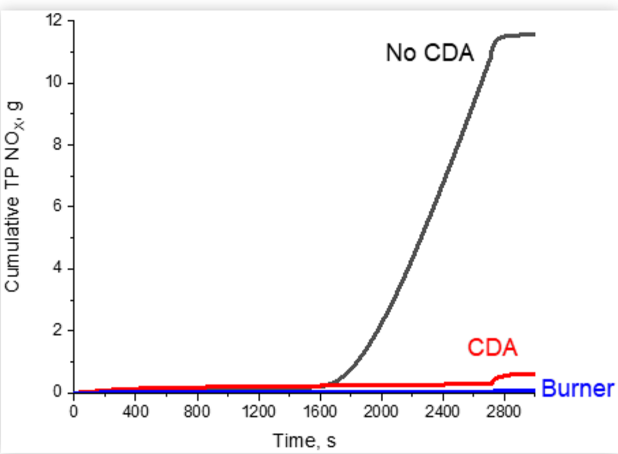


TABLE 7 Average SCR in temperature, TP NO_X, and TP CO_2 over the stay hot tests.

Configuration	AVG SCR In T °C	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr
No CDA / LO-SCR	176	0.518	697
CDA / LO-SCR	186	0.028	624
2-Tier: 300 / 200° C	212	0.003	692

Comparison of Primary AT System with Burner or CDA

A comparison of the burner system relative to a conventional AT system with and without CDA is provided in this section over the NYBC cycle. The comparison data come from testing of a conventional aftertreatment system illustrated in Figure 17 (i.e., the same system architecture as the current test system, shown in Figure 3 above), and an engine equipped with CDA and the capability operate with or without CDA active [17]. Also, the comparison aftertreatment system was only in the degreened state (i.e., it had been subjected to hydrothermal aging, while not to the end of useful life state).

NYBC The NYBC is shown in Figure 18. The cycle consists of an initial 40-minute NYBC followed by a 30-minute idle period. The next 40-minute NYBC is the 'for record' portion and is analyzed for emissions. It is also a lower loaded cycle (8.7% average load). The idle period illustrates the necessity for the AT system to remain hot once it returns to service.

Figure 19 shows the SCR inlet temperature for the NYBC. The first engine setup is with the base aged AT system, with and without the burner. The burner allows for approximately a 50° C increase in exhaust temperature that manifests a significant NO_X reduction for 9.3 grams to 0.8 grams as shown in Figure 20. The burner increases CO_2 by 3.6%, which

FIGURE 17 Reference CDA engine production system.

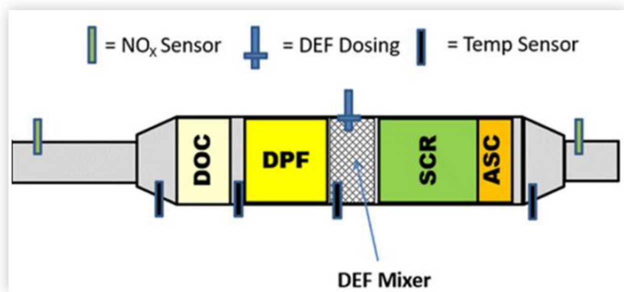


FIGURE 18 NYBC followed by soak and another NYBC.

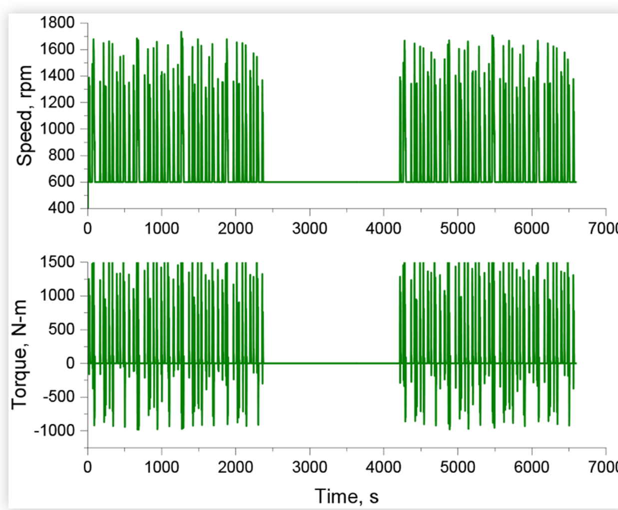


FIGURE 19 SCR Inlet temperature over the NYBC.

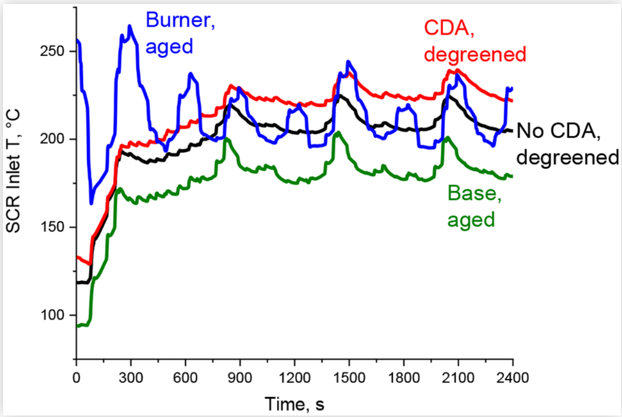
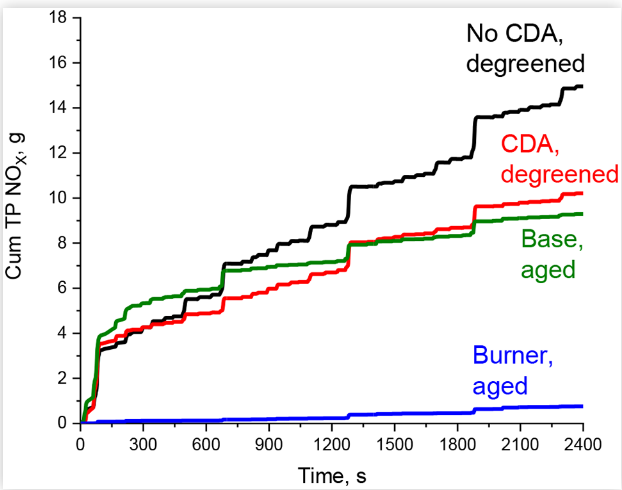


FIGURE 20 TP NO_X over NYBC.



accounts for 2.2 kW-hr of exhaust energy over the cycle, to achieve the 91% NO_X reduction shown in Table 8.

Results for the comparison system are also shown in Figures 19 and 20 and Table 8. The SCR inlet temperature was increased using CDA by approximately 14 degrees, resulting in a 33% NO_X reduction and a 7.8% CO_2 reduction.

The results presented in these last two sections enable a comparison of the burner/conventional AT system and the alternative technology package that includes a dual-injection SCR aftertreatment system and an engine equipped with cylinder de-activation. The burner-based system shows the ability to achieve near zero NO_X emissions on these vocational and low-load cycles, but higher CO_2 emissions were observed in every case. The alternative technology package, and CDA in particular, enables lower NOx emissions an also lower CO_2 emissions on these cycles. Therefore, for the burner-based system to be competitive, further work on the calibration of the burner controls specific to these cycles is needed. This comparison also suggests that the combination of the burner and CDA will enable the lowest overall emissions of both NOx and CO_2.

TABLE 8 NYBC results comparison.

Case	TP NO_X g	$BSCO_2$ g/hp-hr	Est Heat kW-hr
Engine 1			
Base Aged (Primary only)	9.3	642.4	--
Burner+Primary (2-Tier)	0.8	665.4	2.2
Engine 2			
Conventional (without CDA)	15	635.1	--
Conventional (with CDA)	10	585.7	--

Conclusions

The focus of this paper was to show the benefits of adding a fuel burner to a conventional aftertreatment system on vocational and low-load engine test cycles that are very challenging to the conventional system alone. Multiple cycles were tested in order to quantify these benefits. Several different burner control strategies were considered to determine the effect of this aspect on NO_X and CO_2 emissions.

On the Beverage cycle, tailpipe NO_X was reduced using the burner configuration from the based aged system of 2.1 g/hp-hr to near zero (0.001 g/hp-hr). Additional fuel was required, resulting in an additional 13.4% CO_2 emitted. When applied to the LLC, the same burner control strategy reduced the tailpipe NOx from 0.918 to 0.006 g/hp-hr while producing an additional 9.0% CO_2. These results were achieved with a burner control strategy and calibration that provided good NOx performance and no increase in CO_2 emissions on the FTP cycle [9]. The performance of the overall system (burner + conventional aftertreatment system + engine) was not optimized even for that case, much less for the very different nature of the multiple test cycles considered here. Therefore, the results detailed above should not be considered the best that can be achieved with this system.

Test results from an alternative technology package that included CDA on the engine and a LO-SCR added to a primary AT system similar to that employed in this study, were able to be compared to the results from the burner-based system considered in this study. On the LLC, the burner system yielded much lower NO_X at 0.006 g/hp-hr compared to the CDA/LO-SCR system at 0.025 g/hp-hr, while both are significantly lower than the 0.05 g/hp-hr requirement in 2027. The burner system produced an additional 8.4% CO_2 relative to the alternative technology package. This same comparison was made using the stay hot test, which features continuous idling for a significant time. The burner system maintained a target SCR inlet temperature of 200° C (albeit in a cyclic manner) throughout the test, while the CDA system maintained an adequate temperature through the first 20 minutes of idling. The burner yielded 99.9% NO_X reduction but with 10.9% more CO_2 emitted relative to the CDA/LO-SCR system, which yielded a 95% reduction in NO_X.

Finally, a similar comparison of results from the NYBC cycle was considered for the purpose of highlighting the individual benefits of the burner and CDA. Although not a direct comparison, it is clear from the data that CDA and the burner are complementary in nature and thus, in combination, have the potential to enable the lowest NO_X and CO_2 emissions.

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Definitions/Abbreviations

ASC - Ammonia slip catalyst
CARB - California Air Resources Board
CDA - cylinder deactivation
CO_2 - Carbon dioxide
DEF - diesel exhaust fluid
DOC - diesel oxidation catalyst
DPF - diesel particulate filter
ECU - Electronic control unit
EH - electric heater
EO - engine-out
FTIR - Fourier Transform Infrared spectroscopy
FTP - federal test procedure
HD - heavy-duty
LLC - low load cycle
LO-SCR - light-off SCR
NO_X - Nitric oxides

NVH - noise, vibration, and harshness
NYBC - New York Bus Cycle
PNA - Passive NO_X absorber
RPM - revolutions per minute
SCR - selective catalytic reduction
TP - tailpipe
WHTC - World harmonized transient cycle

Appendix

This section provides a short overview of the companion paper [9] for easy comparison highlighting the main results for the burner-AT system on the FTP and WHTC.

The 2-tier strategy of 300 / 200° C provided in this paper and data sets are without insulation on the exhaust system. This section includes the SCR Inlet temperature with and without the burner followed by a table of results for the Cold and Hot cycles of the FTP and WHTC along with the composite test results.

Cold FTP

The 2-tier: 300 / 200° C compare to the base is shown in Figure A1. The burner is on for the first 560 seconds of the cold FTP (not continuously). The burner allows for an average cycle SCR inlet temperature increase of 33° C.

The burner allows for a 61% reduction in TP NO_X emissions with a 1.5% increase in CO_2 emissions (see Table A1).

FIGURE A1 SCR inlet temperature for base and 2-tier burner case over the cold FTP.

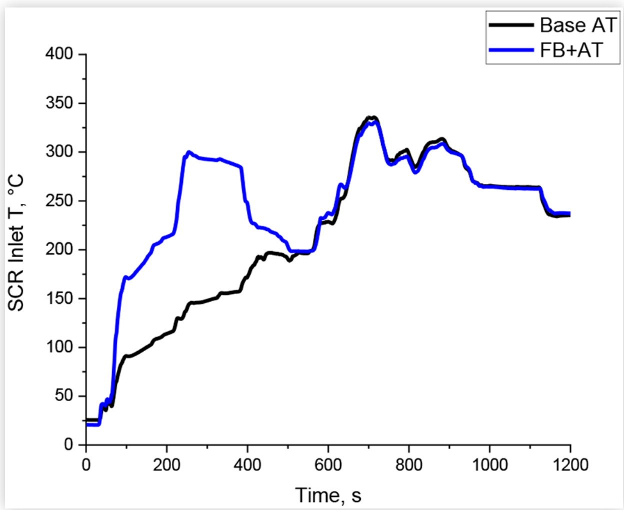

TABLE A1 Results of base compared to burner cases for the cold FTP.

CONFIGURATION	EO $BSNO_X$ g/hp-hr	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr	BURNER $BSCO_2$ g/hp-hr
Base AT	2.178	0.209	524.6	0
2-Tier: 300 / 200° C	2.021	0.094	527.7	15.1
2-Tier: 300 / 200° C (plotted)	2.106	0.082	532.8	14.4

Hot FTP

The 2-tier: 300 / 200° C compare to the base is shown in Figure A2. The burner is on for the first 126 seconds of the hot FTP (near continuously). The burner allows for an average cycle SCR inlet temperature increase of 21° C.

The burner allows for an 87% reduction in TP NO_X emissions with a 0.2% increase in CO_2 emissions (see Table A2). There are various runs with the same burner strategy but with different other configurations such as insulation and dosing strategies.

FIGURE A2 SCR inlet temperature for base and 2-tier burner case over the hot FTP.

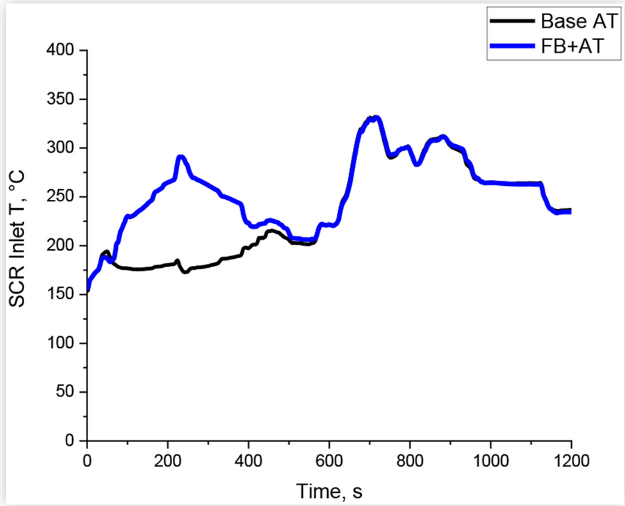

TABLE A2 Results of base compared to burner cases for the hot FTP.

CONFIGURATION	EO $BSNO_X$ g/hp-hr	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr	BURNER $BSCO_2$ g/hp-hr
Base AT	2.740	0.116	503.1	0
2-Tier: 300 / 200° C	2.683	0.032	502.8	7.5
2-Tier: 300 / 200° C	2.708	0.043	507.8	7.9
2-Tier: 300 / 200° C	2.691	0.026	506.5	7.6
2-Tier: 300 / 200° C	2.679	0.018	507.0	7.3
2-Tier: 300 / 200° C	2.634	0.017	508.6	7.6
2-Tier: 300 / 200° C (plotted)	2.635	0.015	504.3	7.2
2-Tier: 300 / 200° C	2.663	0.018	512.3	7.5
2-Tier: 300 / 200° C	2.690	0.015	507.8	7.6
2-Tier: 300 / 200° C	2.726	0.018	508.0	7.5

Composite FTP

Composite calculations for the FTP from the selected cold and hot FTP runs are shown in Table A3. The burner allowed for a composite NO_X reduction of 81% with an increase of CO_2 of only 0.4%. The companion paper [9] discusses the results of insulated exhaust plumbing. One data point was added to Table A3 to reflect the benefit of adding exhaust insulation. The best composite FTP results were achieved with insulation and provided an 82.2% reduction in NO_X while also providing a reduction in CO_2 of 0.2%. The reduction is attributed to the engine exiting warm up strategy faster with the use of the burner. The savings in warm up engine produced CO_2 more than offset the CO_2 produced by the burner.

TABLE A3 Composite FTP emissions values.

Configuration	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr
Base AT	0.129	506.2
2-Tier: 300 / 200° C	0.025	508.4
Comparison to Base AT	−81.0%	0.4%
2-Tier: 300 / 200° C, with insulation	0.023	505
Comparison to Base AT	−82.2%	−0.2%

Cold WHTC

The 2-tier: 300 / 200° C compare to the base is shown in Figure A3. The burner is on for the first 435 seconds of the cold WHTC. It also turns on briefly at 1100 seconds. The burner allows for an average cycle SCR inlet temperature increase of 30° C. The graph shows that the burner keeps the SCR inlet temperature above 200° C for most of the cycle.

The burner allows for an 58% reduction in TP NO_X emissions with a 2% increase in CO_2 emissions (see Table A4) over the cold WHTC.

FIGURE A3 SCR inlet temperature for base and 2-tier burner over the cold WHTC.

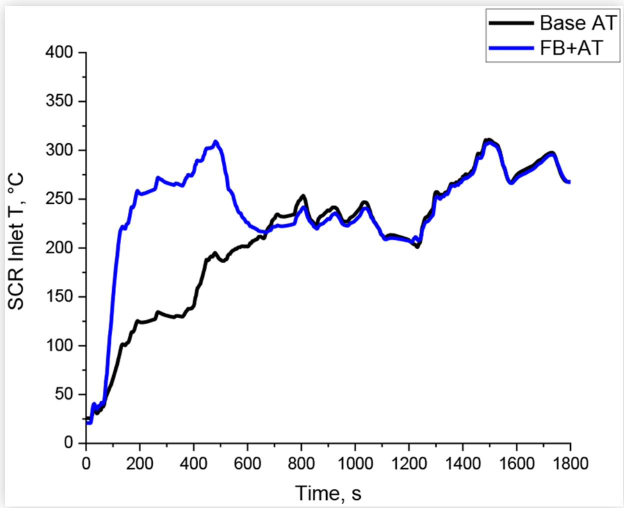

TABLE A4 Results of base compared to burner cases for the cold WHTC.

CONFIGURATION	EO BSNO$_X$ g/kW-hr	TP BSNO$_X$ g/kW-hr	TP BSCO$_2$ g/kW-hr	BURNER BSCO$_2$ g/kW-hr
Base AT	0.232	0.232	676.8	0
2-Tier: 300 / 200° C (plotted)	4.448	0.098	690.5	20.2

Hot WHTC

The 2-tier: 300 / 200° C compare to the base is shown in Figure A4. The burner is on for the first 126 seconds of the hot WHTC. It came on again at 375 seconds for 50 seconds. It came on a third time at 1201 seconds for 32 seconds. The burner allows for an average cycle SCR inlet temperature increase of 22° C.

The burner allows for an 94% reduction in TP NO_X emissions with a 1.8% increase in CO_2 emissions (see Table A5) over the hot WHTC.

FIGURE A4 SCR inlet temperature for base and 2-tier burner case over the hot WTHC.

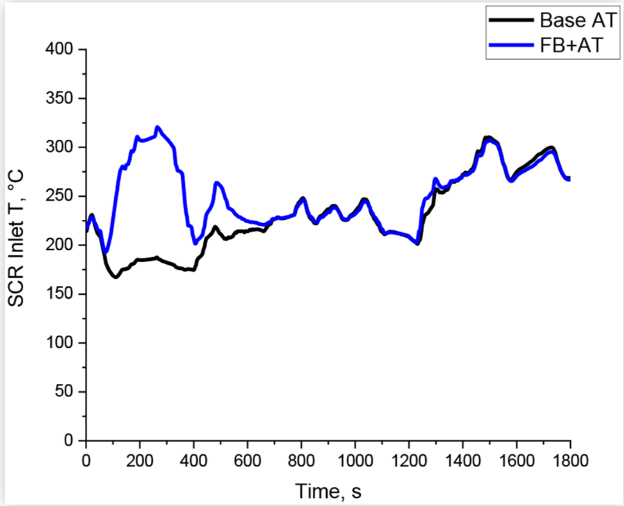

TABLE A5 Results of base compared to burner cases for the hot WHTC.

CONFIGURATION	EO $BSNO_X$ g/hp-hr	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr	BURNER $BSCO_2$ g/hp-hr
Base AT	5.337	0.093	654.1	0
2-Tier: 300 / 200° C	5.280	0.005	672.0	12.2
2-Tier: 300 / 200° C (plotted)	5.327	0.005	666.0	11.3

Composite WHTC

Composite calculations for the WHTC from the selected cold and hot WHTC runs are shown in Table A6. The burner allowed for a composite NO_X reduction of 84% with an increase of CO_2 of only 1.8%.

TABLE A6 Composite WHTC emissions values.

CONFIGURATION	TP $BSNO_X$ g/hp-hr	TP $BSCO_2$ g/hp-hr
Base AT	0.112	657.3
2-Tier: 300 / 200° C	0.018	669.4
Change	−83.7%	1.8%

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