SAE 24PFL-02484

On vs. Off Road Low Load Cycle Comparison

Abstract

Reducing criteria pollutants while reducing greenhouse gases is an active area of research for commercial on-road vehicles as well as for off-road machines. The heavy duty on-road sector has moved to reducing NOx by 82.5% compared to 2010 regulations while increasing the engine useful life from 435,000 to 650,000 miles by 2027 in the United States (US). An additional certification cycle, the Low Load Cycle (LLC), has been added focusing on part load operation having tight NOx emissions levels. In addition to NOx, the total CO_2 emissions from the vehicle will also be reduced for various model years. The off-road market is following with a 90% NOx reduction target compared to Tier 4 Final for 130-560 kW engines along with greenhouse gas targets that are still being established. The off-road market will also need to certify with a Low Load Application Cycle (LLAC), a version of which was proposed for evaluation in 2021. Since the LLAC has not been finalized, this study is being conducted to compare and contrast the LLC for on-road with the LLAC for off-road as there might be some shared learnings. A US off-road production 2023 Fiat Powertrain 13L engine and aftertreatment system was chosen for this work. This engine is used in production for both off-road and on-road products, so it is a good choice for this study. The associated off-road aftertreatment system was aged for more relevant comparisons. The engine calibration was not altered for either of the low load cycles. This study shows that the cycles are quite different in nature as the market needs are different. The LLC includes a large fraction of operation at idle and lower speeds, representing products that use the engine primarily for motive power, where lower vehicle speed means a lower engine speed and load. The LLAC has more time and load spent at high speeds and slightly higher loads. The off-road products represented by this cycle often use the engine to drive auxiliary equipment which means higher parasitic loads and hand/fixed throttle. The comparison will include the use profiles, tailpipe NOx and greenhouse gas emissions (CO_2, N_2O).

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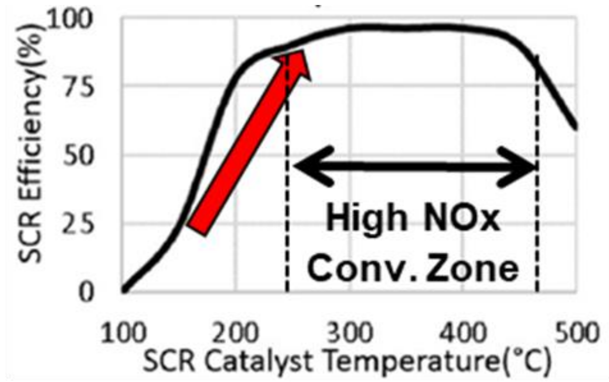
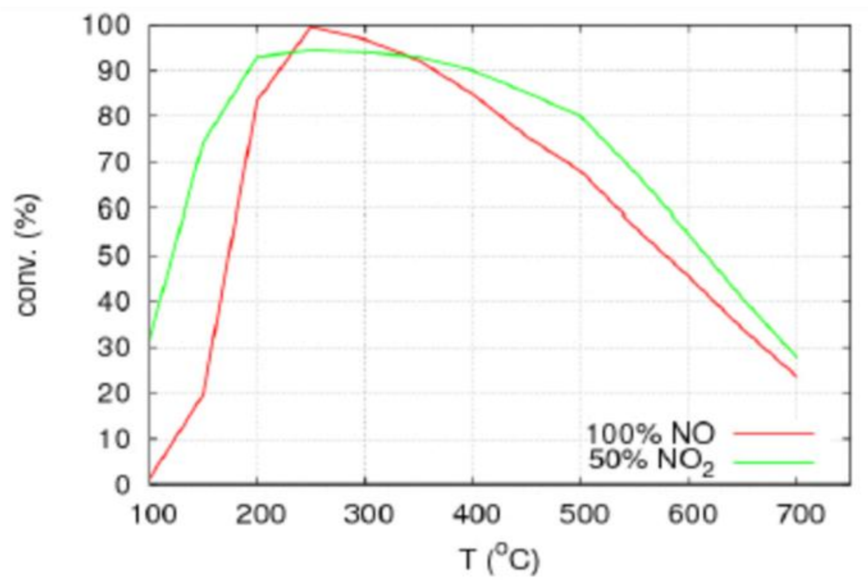
Introduction

Certification of on-road commercial vehicle engines by California Air Resources Board (CARB) requires completion of several test cycles, including the Ramped Mode Cycle (RMC), the FTP cycle and, from model year 2024, the Low Load Cycle (LLC). The LLC is designed to assess NOx emissions during prolonged periods of low load operation [1], such as in urban areas, where air quality is a particular concern. Since exhaust temperatures are reduced at low engine loads, prolonged periods of low load operation eventually reduce the selective catalytic reduction (SCR) device temperature. Figure 1 shows sample SCR NOx reduction curves. Figure 1a shows an increase in NOx reduction as temperature increases up to 300 °C, while Figure 1b separates out NOx in terms of NO and NO_2. Both show that high NOx conversion begins after reaching 250 °C. Specific catalysts used in this study are different than the curves shown in Figure 1, yet the general behavior is expected to be similar.



(a)



(b)

Figure 1: SCR NOx conversion efficiency vs. temperature where Figure 1a shows higher efficiency above 250 °C [3] and Figure 1b shows similar trends [4]

CARB is proposing a revision to the off-road engine certification requirements (Tier 5) for implementation starting in 2029, part of which will incorporate a LLAC for engines 56 – 560kW. The LLAC is designed to represent several low load duty cycles [2].

This paper will compare the on-road LLC and off-road LLAC cycles and provide engine test results for both cycles using a Fiat Powertrain (FPT) 13L Tier 4 Final engine and aftertreatment system. While there are versions of this engine for on-road and off-road application, these tests will use the same Tier 4 Final version of the engine, aftertreatment, and controller calibration for the comparative tests. The on-road and off-road versions of the base engines are very similar, but the on-road aftertreatment (available in the EU, not the US) includes a DPF, whereas the off-road aftertreatment does not include a DPF, as described in the next section.

The 13L engine has not been calibrated to pass either the off-road LLAC or the on-road LLC. The off-road LLAC is not part of a current regulation, and it is a proposed cycle under evaluation. This engine has been specifically developed for off-road applications and this engine has not been certified for the US on-road market. Although FPT makes off-road and on-road engines using similar base parts, these are used for different applications and the engine/aftertreatment systems are calibrated and certified differently. This study uses the same calibration for the off-road LLAC and the on-road LLC which is the off-road engine and aftertreatment calibration.

The objective of this study is to compare and contrast the engine operation and emissions for the off-road LLAC and on-road LLC. The experimental setup will be shared for the engine and aftertreatment systems. An analytical comparison on the LLAC and LLC cycles is included along with a description of cycle generation. The test procedure used, which includes the pre-conditioning cycles, is described. Emission results for NOx, N_2O, CO_2 and NH_3 are compared. Finally, critical gas temperatures in the aftertreatment system at inlet to the diesel oxidation catalyst (DOC) and in and out of the Selective Catalytic Reduction (SCR) catalyst are compared.

Experimental Setup

This section will cover the engine specifications and test cell setup. This includes the equipment used with the engine, aftertreatment (AT) and instrumentation.

The LLAC and LLC testing was performed on an off-road production engine. The FPT Cursor 13 has a displacement of 12.9 liters. The engine retained its stock configuration including the air handling and fueling. Table 1 shows the key specifications for this off-road engine, including the rated power of 407 kW at 2100 rpm. The stock off-road calibration was used for both the LLAC and LLC.

Table 1: Engine Specifications

Cylinders	6L
Turbocharger	Wastegate
Injection System	Common Rail
Displacement	12.9 liters
Bore x Stroke	135 mm x 150 mm
Rated Power	407 kW @ 2100 rpm
Maximum Power	425 kW @ 1920 rpm
Max Torque	2450 Nm @ 1400 rpm
Certification	US Stage IV / Tier 4 Final
EGR System	None

Figure 2 shows the published torque curve of the Cursor 13 engine. A torque curve generation was run to establish the maximum engine torque and power for the purpose of cycle generation. This torque curve generation is plotted alongside the published torque curve.

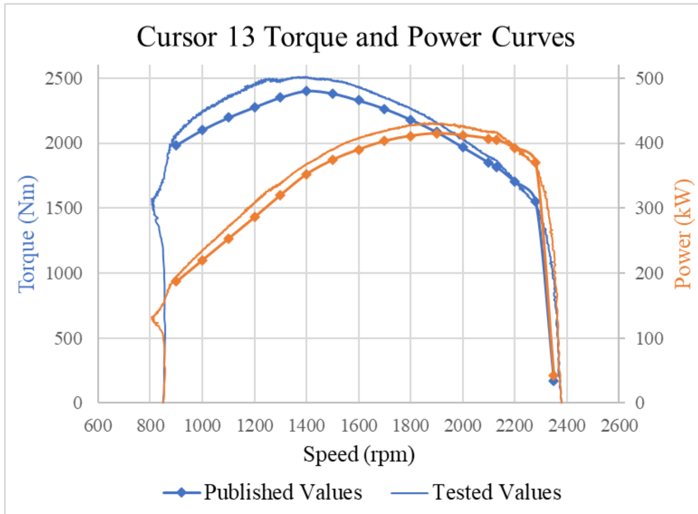


Figure 2: Published and generated torque curves

An 800 hp AVL Dynoforce Dynamometer was used to control engine speed and engine torque. The ratings of this Dyno are listed in Table 2.

Table 2: Dyno specifications

Maximum Speed	4500 rpm
Transient Speed Gradient	9700 rpm/s
Nominal Torque	3800 Nm @ 0-1800 rpm
Overload Torque	4560 Nm @ 0-1800 rpm
Nominal Power	700 kW @ 1800-3600 rpm
Overload Power	840 kW @ 1800-3000 rpm

Figure 3 shows the intake of the engine, which was equipped with a Laminar Flow Element (LFE). The LFE was located near the front-right corner of the engine to ensure consistency and uniformity in the airflow entering the compressor and allowing for measurement of the intake air flowrate. The air was passed through a series of charge air coolers after being compressed.

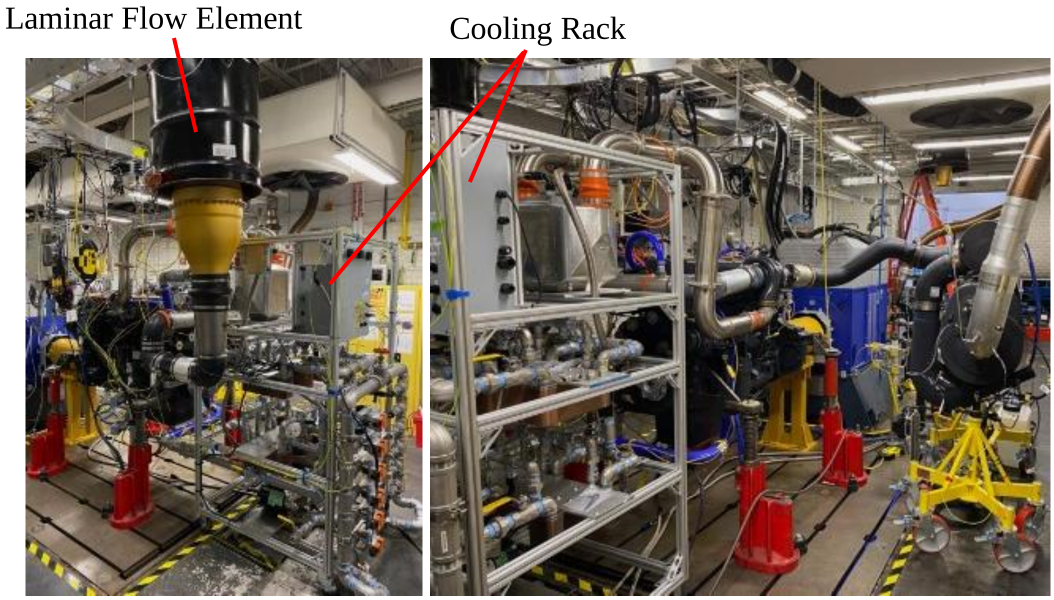


Figure 3: Cooling rack and Laminar Flow Element

Fuel supply and return were measured with two Micro Motion ELITE Coriolis flow meters. The flow meters are shown next to the Dyno in Figure 4.

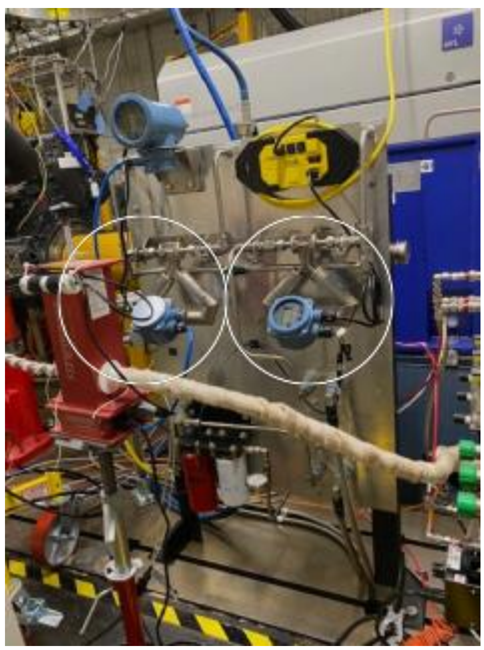


Figure 4: Fuel flow meters

Figure 5 shows an exhaust throttle valve immediately downstream of the turbine. This valve was controlled by the engine control unit (ECU) to alter the exhaust backpressure and to control AT temperature during cold starts. The exhaust throttle valve partially closes during cold start and idle period to raise the diesel oxidation catalyst (DOC) to a target temperature of 250 °C.

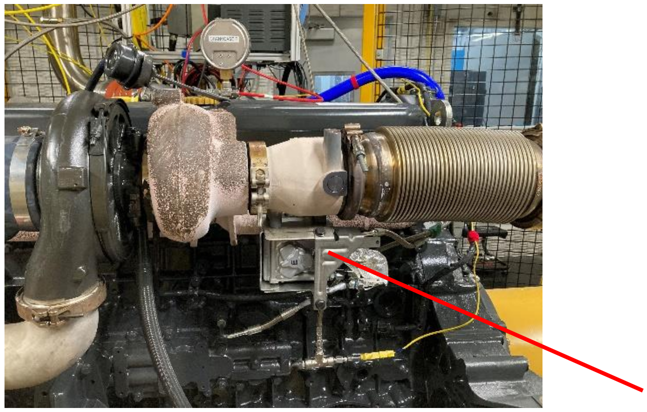


Figure 5: Turbocharger and exhaust throttle valve

Figure 6 shows the engine exhaust entering a dual-path SCR downstream of a separately canned DOC. Urea dosing occurs in the same can immediately downstream of the DOC. There is no Diesel Particulate Filter (DPF) on this AT. The AT was mounted on its side (as shown on the left) in the test cell, as it did not fit if installed vertically. Shown on the right is a schematic view of the AT, highlighting airflow direction within the dual-path system. After entering the SCR can, exhaust splits to flow through SCR Bank 1 and Bank 2. The outlet of the SCR Bank 2 flows directly to the tailpipe. The outlet of SCR Bank 1 exhaust reverses direction in a pair of bypass pipes, then flows to the tailpipe.

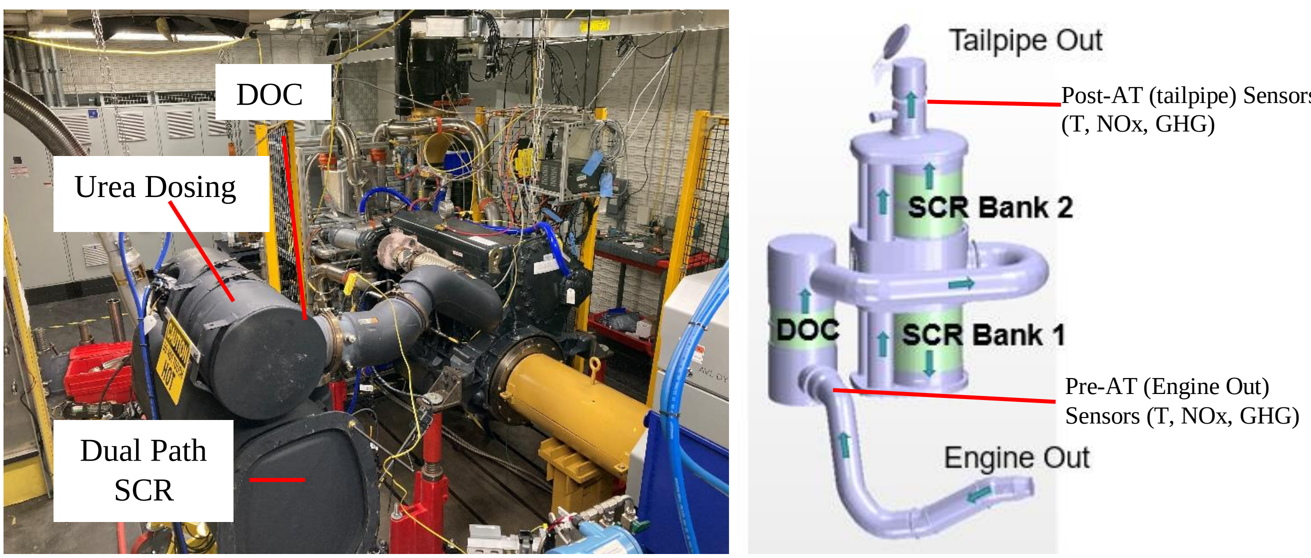


Figure 6: Engine and aftertreatment (left) and aftertreatment flow pass schematic (right)

The exhaust pipeline has locations both upstream and downstream of the AT for measurement of temperature and emissions sampling. Sensors upstream of the AT are used to measure engine-out emissions and temperature. Several more sensors downstream of the SCR are used to measure tailpipe emissions and temperature. Emission measurements are made pre- and post-AT with the devices listed in Table 3 below.

Table 3: Emissions instrumentation by location

Location:	Measurement:	Sensor:
Engine-Out	NOx	MKS MultiGas 2030 FTIR Gas Analyzer
	THC	CAI 600 Series HFID
	CO/CO_2	MKS MultiGas 2030 FTIR Gas Analyzer
Tailpipe	NOx	MKS MultiGas 2030 FTIR Gas Analyzer & CAI 700 Series HCLD
	THC	CAI 600 Series HFID & CAI 700 Series HFID
	CO/CO_2	MKS MultiGas 2030 FTIR Gas Analyzer & CAI 600 Series NDIR
	NH_3	MKS MultiGas 2030 FTIR Gas Analyzer
	O_2	CAI 600 Series Paramagnetic

Hydrothermal aging of the AT was conducted at Southwest Research Institute. The AT was hydrothermally aged for 80 hours at 519 °C, corresponding to the thermal load encountered by a representative field vehicle. Temperature profiles from five vehicles are shown together in Figure 7, showing that the dominant SCR operating zone is at high temperature.

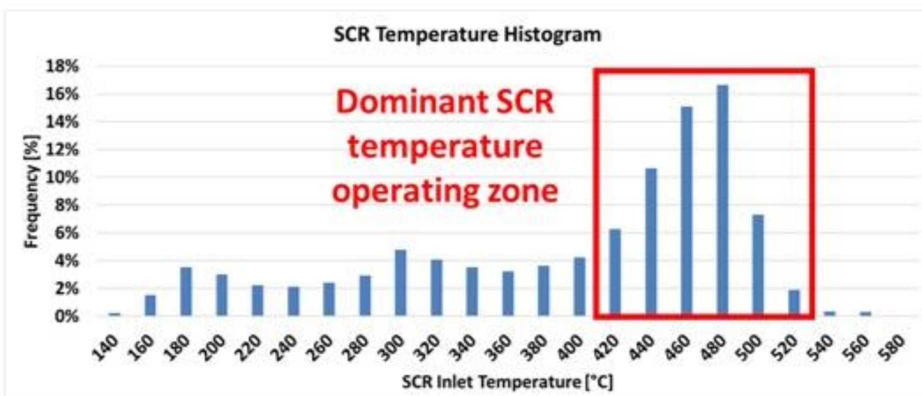


Figure 7: SCR temperature operating frequency for a representative off-road vehicle

Analytical Cycle Comparison for On Vs. Off Road

This section will discuss generating the two low load cycles using a published torque curve for the Cursor 13L engine and following the federal regulations to de-normalize the given speed and torque values. The on-road and the off-road cycles were generated using the equations and procedure provided below. The two low load cycles were compared to each other, and several differences were observed regarding their operational range discussed in detail later in the section.

Cycle Generation

The on-road LLC and the off-road LLAC were developed using the torque curve shown above in Figure 2. The most recent cycle patterns were obtained from DieselNet and de-normalized for the Cursor 13 engine. The Code of Federal Regulation (CFR) article 1065.610 [5] was utilized for duty cycle generation. The key equations for cycle generation are shown below.

$$n_{ref} = \%\,\text{speed} * \left(f_{n,test} - f_{n,idle}\right) + f_{n,idle} \quad (1)$$

Equation 1 is used to calculate n_{ref} which is the Reference Speed; % speed is the normalized speed provided, $f_{n,test}$ is the Maximum Test Speed (MTS), and $f_{n,idle}$ is the idle engine speed.

$$T_{ref} = \%\,\text{torque} * T_{test} \qquad (2)$$

Similarly, T_{ref}, reference torque can be calculated using equation 2 where % torque is normalized torque provided and T_{test} is the maximum torque at the corresponding speed.

The same procedure was used to generate the on-road and off-road low-load cycles. The maximum Test Speed (MTS) or $f_{n,test}$ in Equation 1 was calculated using the power curve shown in Figure 1. The steps to get MTS are as follows:

1. Determine the maximum engine power and calculate 98% of that.
2. Establish the highest and lowest corresponding engine speeds at 98% of max engine power.
3. Find the average of the two speeds, this will be the speed at max power.
4. Transform the map into a normalized power-versus-speed map by dividing the power terms by maximum power and the speed terms by the average speed calculated at max power.
5. Utilize the normalized map to calculate a quantity known as the sum of squares which is the normalized speed and power values squared and added together.
6. Determine the maximum value for the sum of the squares from the map and find 98% of the maximum SOS value.
7. Use that value to get the corresponding lowest and highest engine speeds.
8. Finally, calculate the average of those two speeds. That is the maximum test speed used to de-normalize any duty cycle.

A MATLAB script was written to perform the cycle calculation discussed above. The script utilized the published torque curve, interpolated for torque and power values for every 0.1 rpm. This level of resolution was required as 1 rpm was not precise enough to capture the values needed. The script de-normalized the normalized published cycles using the equations discussed above. The two low-load cycles were generated and plotted for detailed comparison.

Cycle Comparison

Figure 8 below shows the two low-load cycles on top of each other. The plot on the top is the speed in rpm and the bottom plot is torque in Nm. The blue curve is the off-road LLAC and the orange curve is the on-road LLC. Key differences can be observed in Figure 8. First, the LLC (5505 seconds) is longer than LLAC (4337 seconds). Second, the off-road cycle operates at higher speed and torque values for a longer time compared to the on-road cycle.

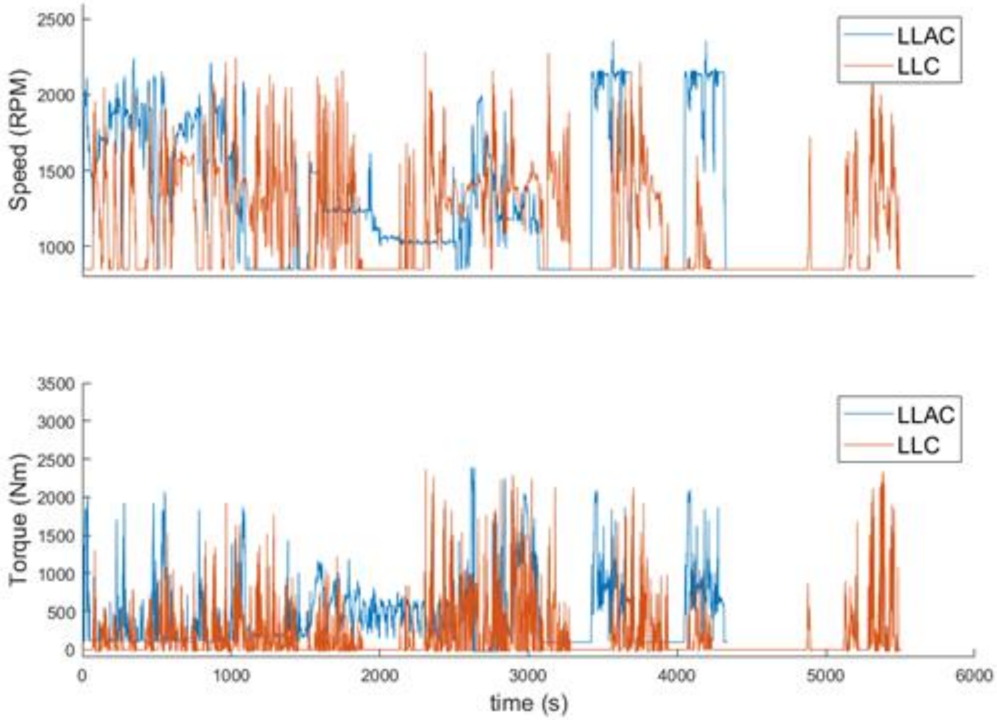


Figure 8: Engine speed and torque for on-road and off-road low load cycles

The cycle speed and torque points were plotted along with the engine torque curve to identify the regions where the two cycles operate to investigate the differences further. Figures 9 and 10 show the off-road and on-road cycles vs. the torque curve respectively. The off-road cycle operates at higher torque as multiple points lie on the torque curve, hitting some of the highest possible torque values. The on-road cycle shows a much higher density of operating points within the lower torque regions including negative torque values.

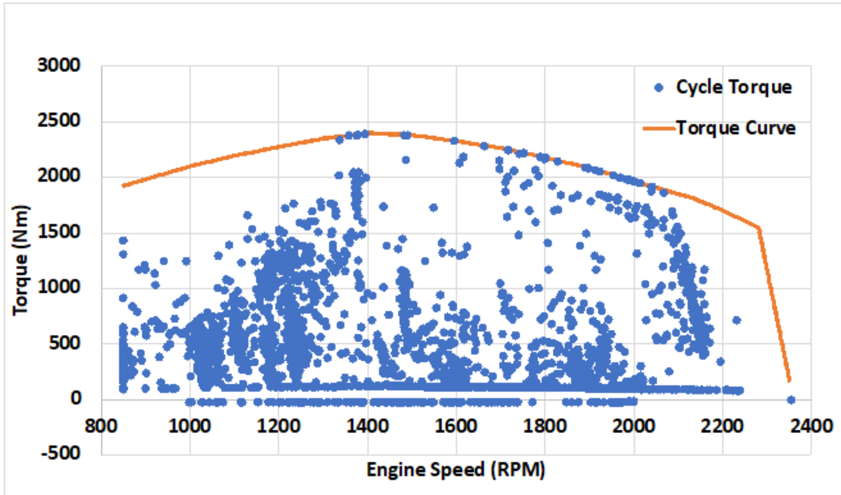


Figure 9: LLAC operating point relative to torque curve

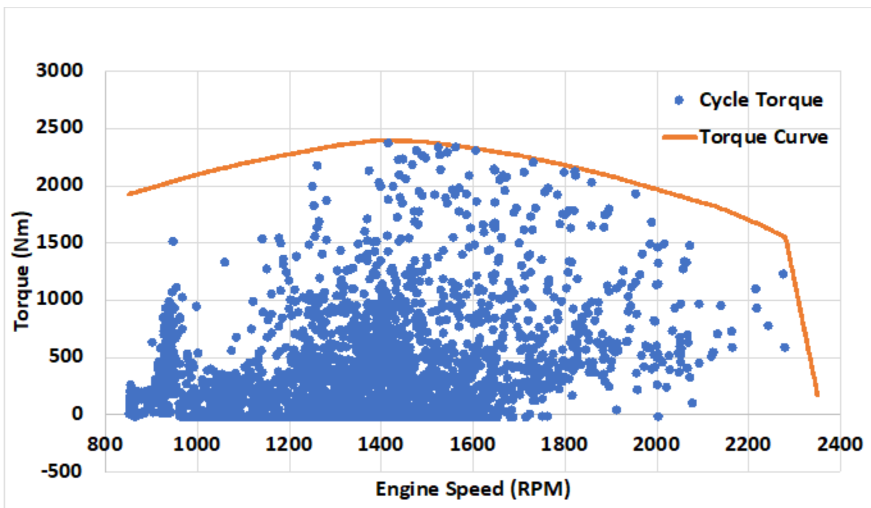


Figure 10: LLC operating point relative to torque curve

Similarly, an analysis was done to quantify how many times a certain speed or torque value occurs in the two cycles. The plots below show specific speed and torque regions where each cycle operates more frequently.

Figure 11 shows the percentage of time spent in particular speed ranges over the cycles. The on-road cycle operates in lower-speed regions for much longer than the off-road cycle, barely touching the speeds above 2100 rpm, whereas the LLAC spends a considerable amount of time at the higher speeds. The on-road cycle operates for over 58.5% of the time at speeds between 800 rpm and 1200 rpm (3219 seconds) with an additional 33.5% between 1200 rpm and 1600 rpm (1844 seconds). Moreover, the on-road cycle only runs for 8% of the time above 1600 rpm. The off-road cycle also operates in lower speed regions; however, it spends 32% of the time above 1600 rpm.

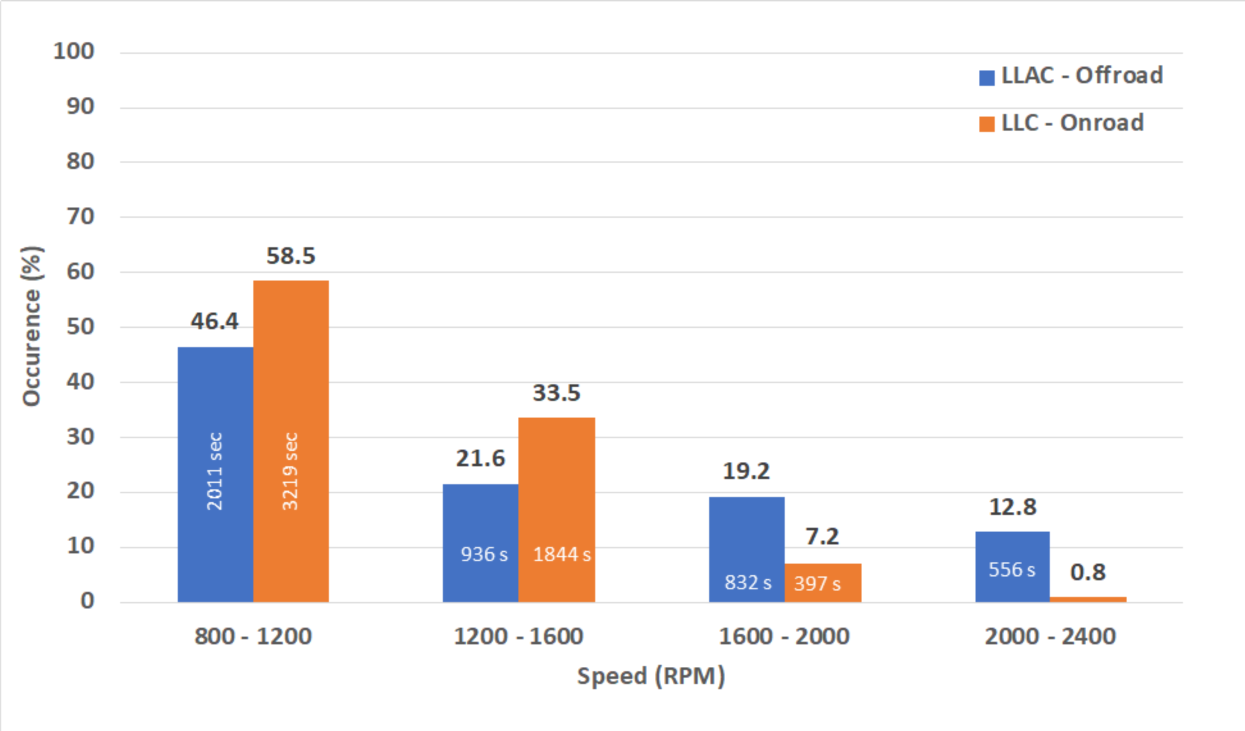


Figure 11: Cumulative Engine Speed Distributions for LLAC and LLC

Similarly, Figure 12 shows the fraction of time spent in particular torque ranges for both cycles. The on-road cycle motors for 15% of the cycle vs. 3.8% for the off-road cycle. Both cycles spend about 70% of the time between zero and 500 Nm (73.8% for on-road and 69.1% for off-road). A deeper analysis of this torque region (0 to 500 Nm) shows that the on-road cycle runs at zero torque for over 3100 seconds, which is about 56% of the cycle time and almost double the amount of time spent in the off-road cycle at 1700 seconds. The on-road cycle operates in the higher torque regions for 4.7% of the cycle time, whereas the off-road cycle spends 27.2% of its time at torques above 500 Nm. Thus, Figures 11 and 12 quantitatively demonstrate that the LLAC includes a high fraction of high speed and high load operation compared to the LLC.

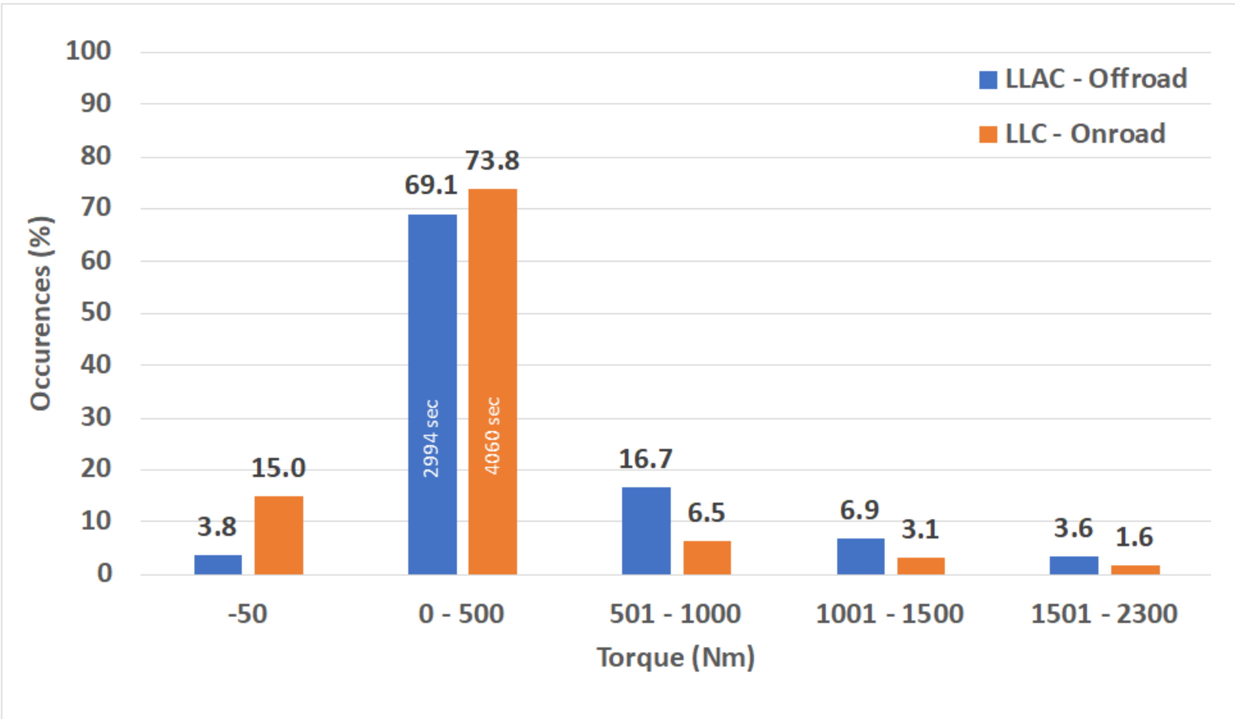


Figure 12: Cumulative Engine Torque Distributions for LLAC and LLC

Test Procedure

The 13 engine and AT system were tested at Oak Ridge National Laboratory. The engine was broken in following a 2-hour break-in procedure provided by FPT, and an additional 40 hours of engine operation took place prior to testing. The AT was hydrothermally aged for 80 hours at 519 ℃ as described above. A torque curve was generated to map the engine. The torque curve generation included engine warm-up, measuring idle speed, ramping the engine to 100% load, and measuring the full load curve. This torque curve was used to compute the off-road LLAC and on-road LLC for this testing, as described above.

The two low-load cycles were repeated two times each to ensure repeatability and accuracy. Before running the low-load cycles, one cold and two hot Non-Road Transient Cycles (NRTC) were performed with a 20 minute soak between each cycle as a pre-conditioning.

Results

The overall cycle results are provided in Table 4. A detailed analysis of the off-road LLAC is next, followed by the on-road LLC using multi-tiered figures (Figures 13 and 14). The LLAC and LLC are plotted together in Figure 15 to highlight differences. The later portions (post 3000 seconds) of each cycle are interesting and highlighted next (Figures 16 and 17). Finally, a greenhouse gas (GHG) analysis is provided (Figure 18) followed by overall NOx conversion efficiency (Figure 19).

Table 4 shows the emissions and cycle summary for the LLAC and LLC cycles. It should be noted that the off-road LLAC is not currently regulated, and the on-road LLC is being run using an engine with an off-road calibration. However, interesting comparisons can be made. The results show significant differences in the NOx emissions between the two cycles. The cycle work is 75% more with the LLAC than the LLC, while the LLAC fuel consumption is 40% more. Although the LLAC demands much higher work, the LLAC brake specific NOx emissions are 80% less and the brake specific CO_2 emissions are 18% less. Details of each cycle follow.

Table 4: Cycle Statistics for the LLAC and LLC

	off-road LLAC	on-road LLC	% increase (LLAC relative to LLC)
Cycle Work, kWhr	81.5	46.7	75%
Fuel Consumption, kg	19.3	13.8	40%
NOx, g/kWhr	0.173	0.861	-80%
NH_3*, g/kWhr	0.0043	0.0026	
N_2O*, g/kWhr	0.149	0.159	
CO_2, g/kWhr	817.6	994.3	-18%

measured by FTIR

Figure 13 shows a multi-tiered characterization of the LLAC. Engine speed and torque are shown first followed by engine out NOx and tailpipe NOx. Next, cumulative graphs of tailpipe N_2O, NH_3, NOx, CO_2 and fuel are provided. The key temperatures follow with DOC inlet and SCR inlet and outlet gas temperatures. Finally, the exhaust flap position, located immediately downstream of the turbocharger, is shown.

General observations from the LLAC are that the AT greatly reduces the engine out NOx, as shown by the very low tailpipe NOx ppm throughout the cycle. Cumulative GHG emissions are characterized with N_2O exceeding about 10 grams and CO_2 over 6000 grams. It is noteworthy that N_2O has a global warming potential of 273 times that of CO_2. As expected, cumulative CO_2 and fuel use track proportionally. The SCR temperature remains in a good operating range of approximately 250 to 300 °C enabling the effective the NOx reduction. Finally, the exhaust flap remains active during the LLAC for the purpose of increasing DOC and SCR temperatures to remain in the highly effective range. In summary, the production engine calibration reduces NOx effectively over the LLAC cycle.

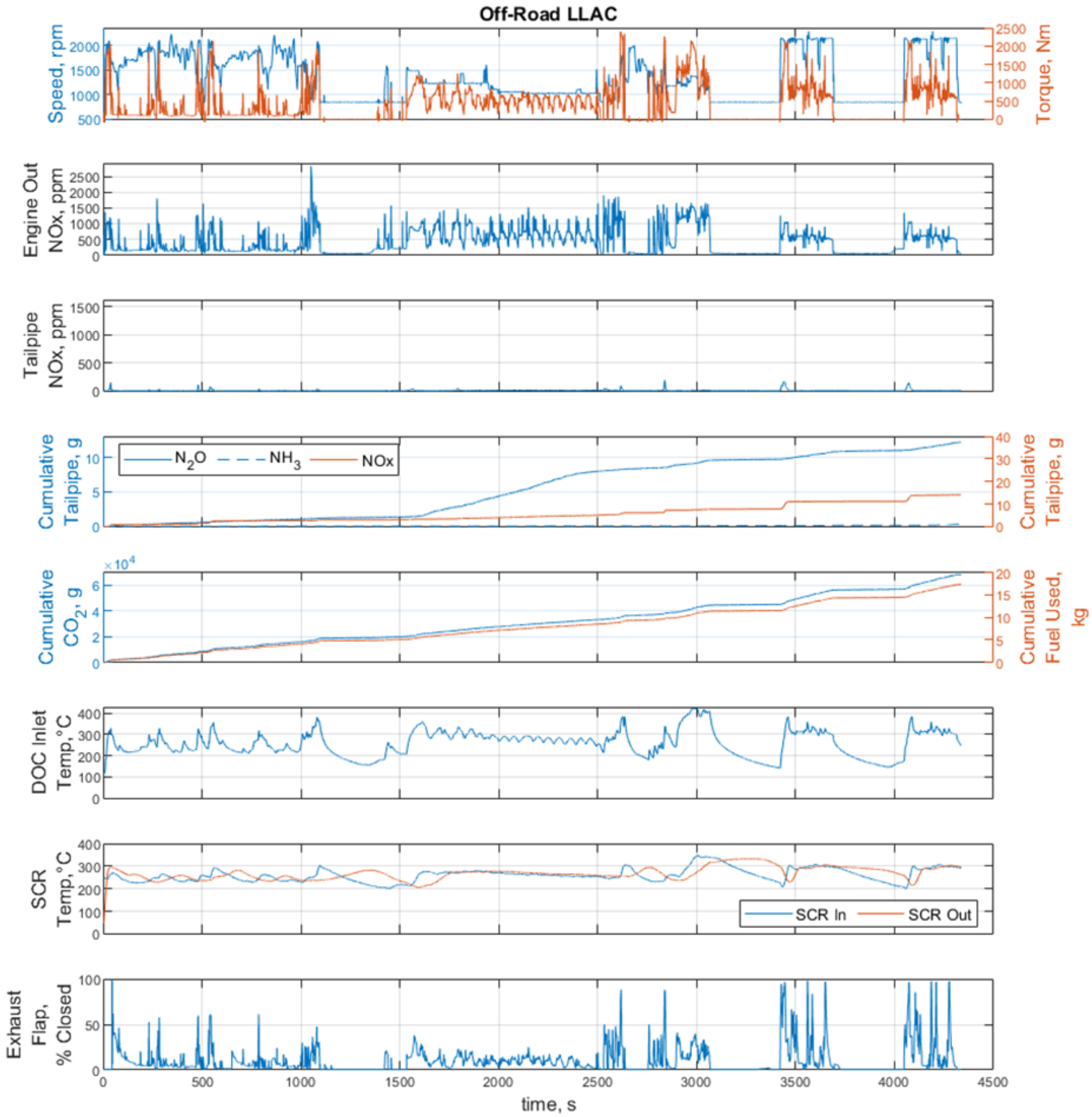


Figure 13: Off-Road LLAC Cycle Characterization

Figure 14 shows the same format multi-tiered characterization for the LLC. General observations from the LLC are that engine out NOx is reduced greatly as shown by the very low tailpipe NOx ppm up until the long idle portion of the cycle at around 4300 seconds. This is attributed to the SCR temperature dipping below 200 °C resulting in low NOx reduction performance. Typically, an on-road configuration would have a DPF while this system does not. Perhaps the DPF would retain enough heat to keep the SCR warmer at the end of the cycle, although the warm-up portion with a DPF could yield more NOx slip. However, this system does not have DPF, so it will be assessed without one. GHG emissions are characterized with N_2O exceeding about 12 grams (higher than LLAC) and CO_2 under 6000 grams (less than LLAC). As expected, cumulative CO_2

and fuel used track proportionally. The SCR temperature remains in a good operating range of approximately 200 to 300 °C which is why the NOx reduction is highly effective up until the long idle portion of the cycle (approximately 4000 sec) when SCR temperatures dip below 200 °C resulting in significant NOx slip. Finally, the exhaust flap remains active during a much larger portion of the LLC for the purpose of increasing DOC and SCR temperatures. The exhaust flap is effective until the last idle period where the SCR temperature drops. It should be noted here that more aggressive flap use in these later regions of operation is a likely calibration strategy in response to the introduction of low load cycle requirements. NOx conversion performance at the end of the LLC degrades due to the lower SCR temperature followed by a high load engine operation resulting in NOx passing out the tailpipe.

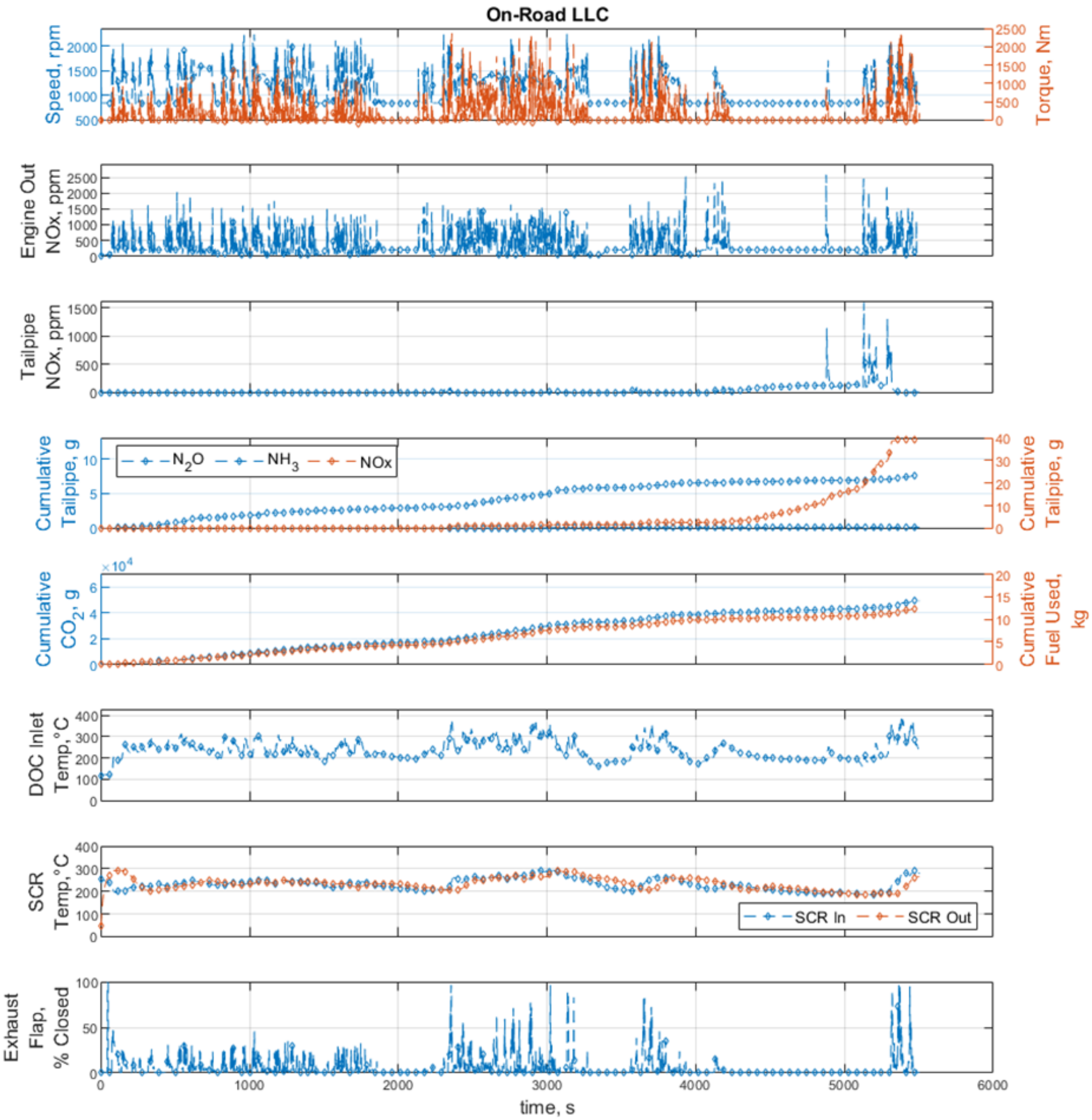


Figure 14: On-Road LLC Cycle Characterization

Figure 15 shows an overlay comparison of the LLAC and LLC. The LLAC is a shorter cycle than the LLC as shown by the top two plots of the figure with engine speed and torque. At 4500 seconds (duration of LLAC), the LLC cumulative NOx is less than half of the cumulative total for the LLAC. However, the NOx spikes after 4500 seconds in the LLC cycle make a large contribution to the total NOx slip, eventually exceeding total NOx emissions of the LLAC by a factor of three. The largest difference in NOx is due to the SCR temperatures being maintained from 250 to 300 °C for the LLAC while the LLC drops to 200 °C after 4000 seconds into the cycle.

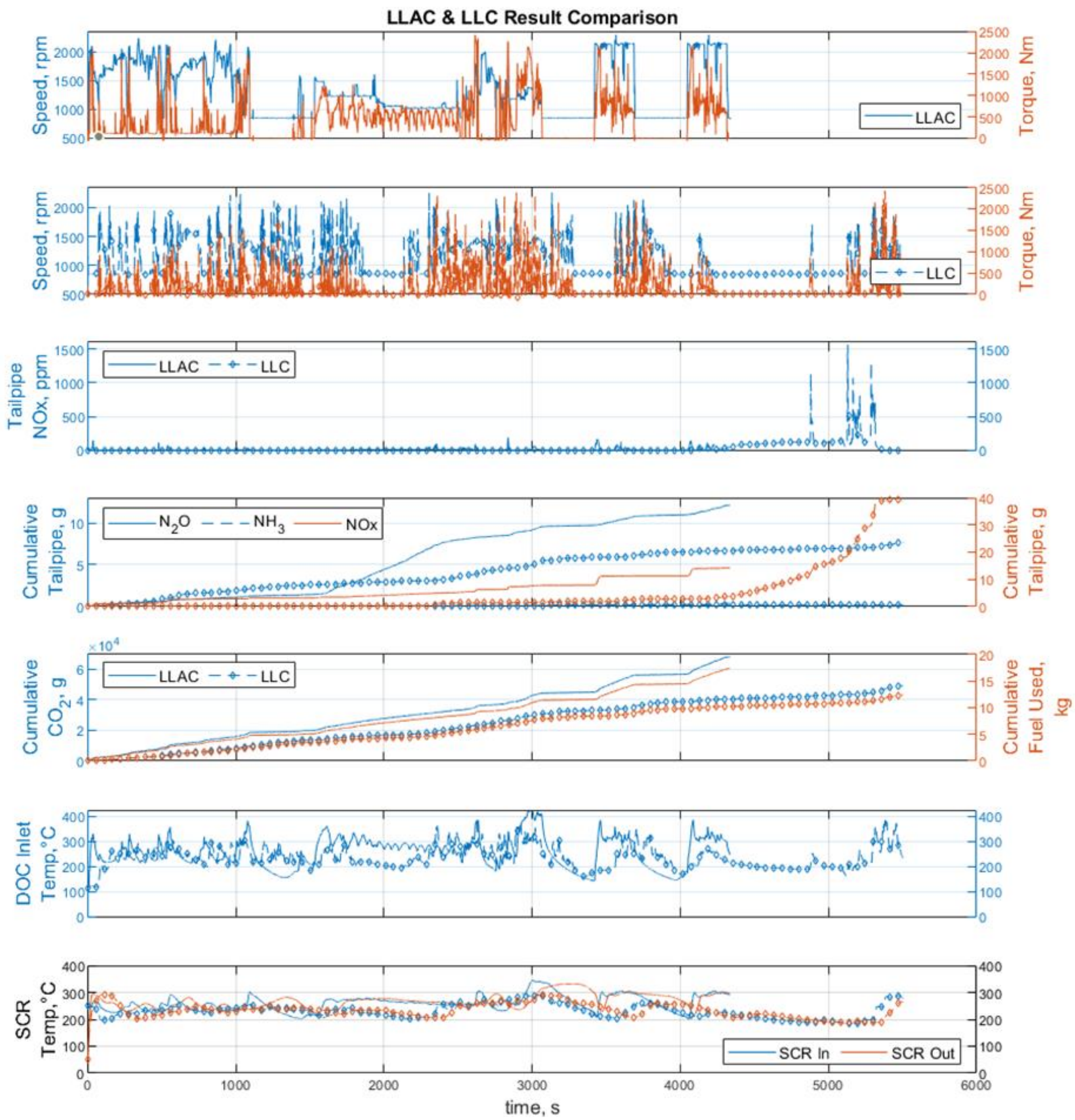


Figure 15: Differences between LLAC and LLC

Referring to Table 4 and Figure 15, the higher cycle work and corresponding higher engine out NOx are inconsistent with the overall cycle results, as the tail pipe NOx differences are dominated by the LLC tailpipe NOx emissions from 4000 sec to the end of the cycle. Over 93% of the tailpipe

NOx emissions occur after 4000 sec in the LLC, compared to 45% of the tailpipe NOx emissions after 3150 sec in the LLAC (representing the same proportion of time). As a comparison, 22% and 33% of the engine out NOx occurs after these points in the LLC and LLAC respectively.

A deeper look into the later portions of the LLAC and LLC cycles is shown in Figures 16 and 17, respectively, to understand the root cause of the NOx breakthrough. While there is no direct measurement of the SCR catalyst temperature, the temperature can be established by looking at the SCR in and SCR out temperatures. During the LLAC (Figure 16) the SCR gas inlet temperature drops from 300 °C to 200 °C as the cycle progresses from 3150 sec to 3415 sec. This is due to the low heat input during low load operation. The cold exhaust stream cools the upstream portions of the exhaust system, as shown by the DOC inlet temperature dropping to 145 °C. However, the SCR inlet temperature stays above 200 °C due to the DOC thermal inertia, and the SCR gas outlet temperature stays at approximately 330 °C due to the thermal inertia of the SCR itself. Once the load increases at 3415 sec, the DOC inlet and SCR inlet temperatures increase rapidly due to the higher load and higher exhaust temperatures, but the SCR outlet temperature drops as the cooler upstream section of the SCR acts to cool the downstream section of the SCR catalyst. Eventually, the SCR gas outlet temperature rises after approximately 60 sec as the hotter exhaust gas passes through and heats the SCR. Throughout all of these temperature transients, sections of the SCR catalyst are still at a temperature sufficient to convert NOx.

This contrasts with the extended idle period of the LLC shown in Figure 17, where the temperature of gas flow throughout the aftertreatment system is fairly consistent from 4400 sec to 5200 sec. The SCR inlet and outlet temperatures hover around 200 °C from 4200 sec until 5300 sec which results in low NOx conversion efficiency and a long period of NOx breakthrough. Furthermore, when the load increases at 5300 sec, the SCR temperature is slow to increase, and additional NOx is released.

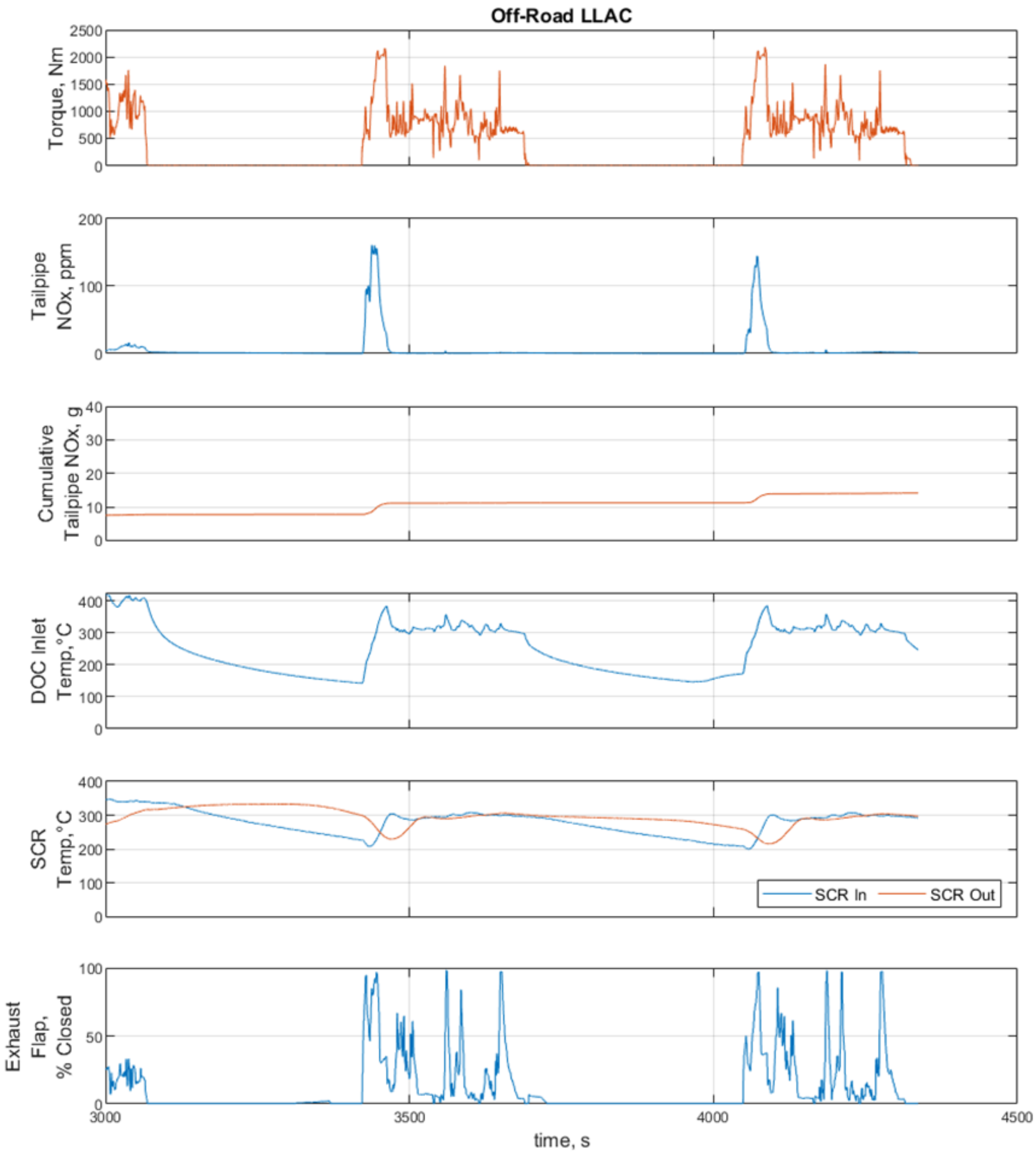


Figure 16: Root Cause of NOx Breakthrough on LLAC

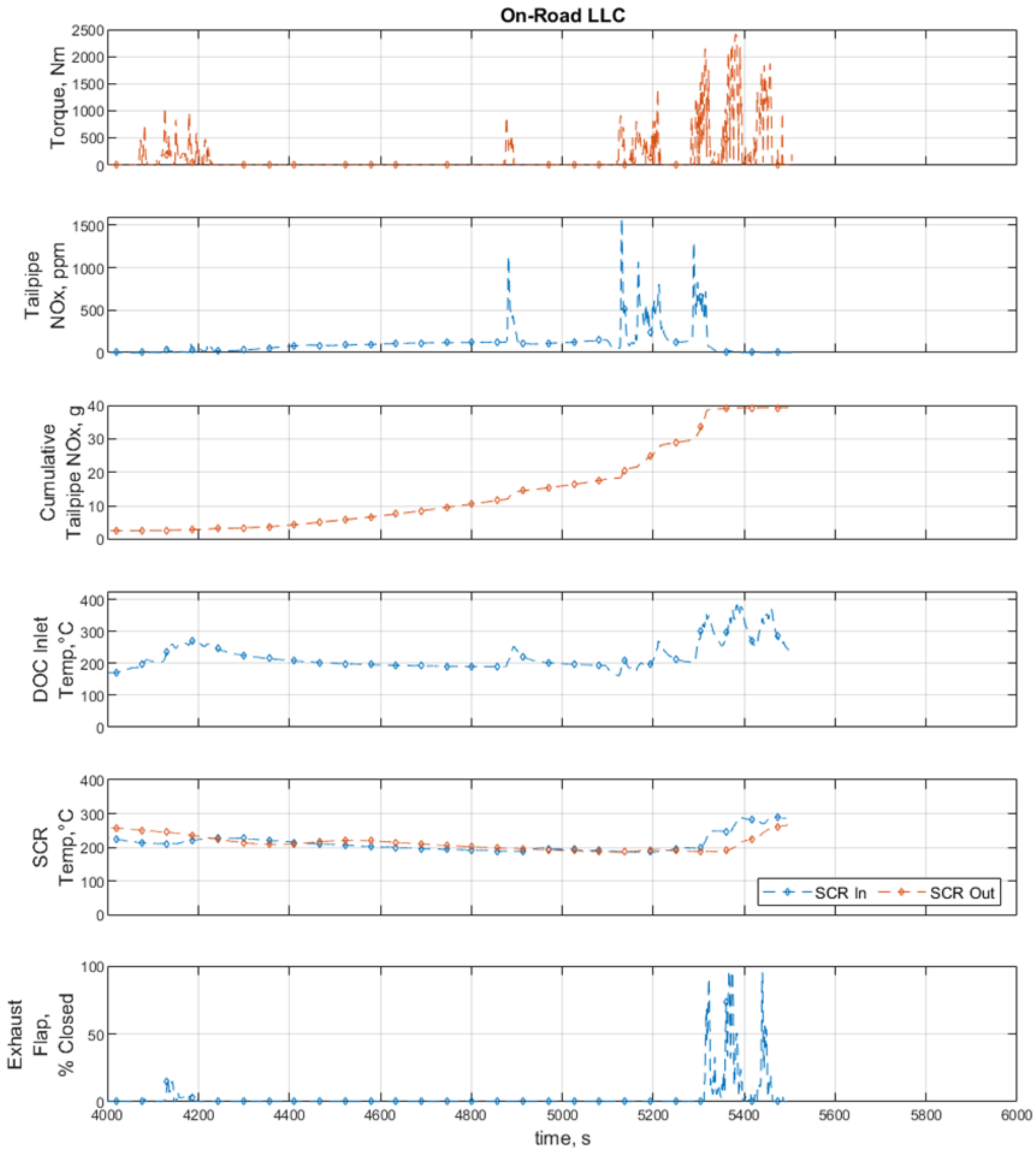


Figure 17: Root Cause of NOx Breakthrough on LLC

Figure 18 shows the GHG results for the LLAC and LLC quantified in terms total grams of CO_2 emissions while Table 4 showed these in terms of brake specific emissions. The GHG potential of N_2O is 273 times more than CO_2. The cycles are compared on a CO_2-equivalent basis. N_2O emissions contribute roughly 5% of GHG emissions from both the LLAC and the LLC. The LLAC has higher total CO_2-equivalent GHG emissions than the LLC; however, the cycle work is 75% higher.

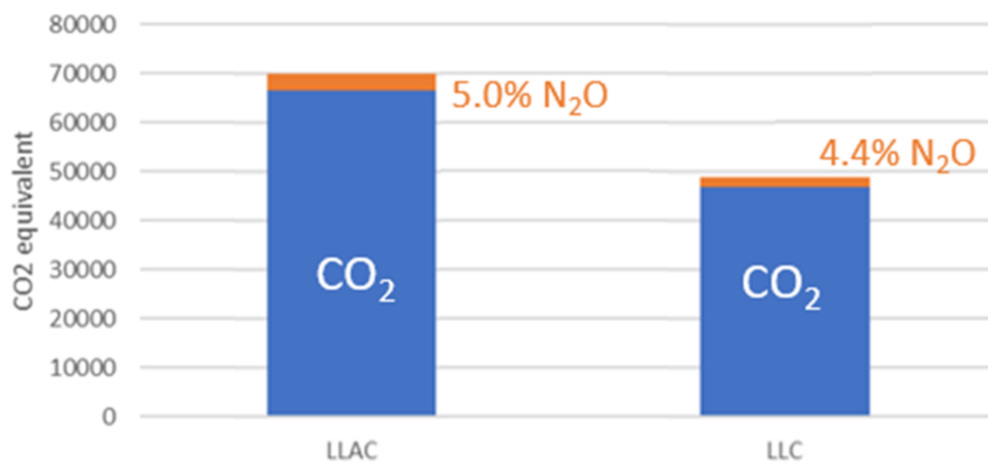


Figure 18: Greenhouse Gas Characterization

N_2O can be formed over all the components of the AT system: DOC, SCR, and ammonia slip catalyst (ASC). N_2O formation over DOCs usually occurs at low temperatures (<200 °C) due to interactions between engine-out NOx and hydrocarbon species on the catalyst surface and is typically only observed during cold start operating conditions. This mechanism does not appear to significantly contribute to N_2O formation for either the LLAC or the LLC as the DOC temperatures are not in the range expected to generate N_2O.

N_2O can also be formed over the SCR catalyst. Most SCR catalyst formulations have a low but non-negligible selectivity to N_2O (instead of N_2). Higher levels of engine-out NOx will therefore result in higher production of N_2O. SCR selectivity to N_2O is a strong function of NO_2/NOx ratio in the SCR feed - higher ratios of NO_2 will generate higher levels of N_2O, especially when NO_2/NOx exceeds 0.5. Finally, N_2O can also be generated by NH_3 oxidation over the ASC. Higher levels of NH_3 slip from the SCR catalyst will generate more N_2O over the ASC.

The higher total mass of N_2O generated over the LLAC as compared to the LLC (Figure 15) is due to the increased work and higher associated total mass of engine-out NOx emissions, a small fraction of which is converted to N_2O. The normalized N_2O generation (Table 4) is similar between the two cycles. Since N_2O has such a high global warming potential, it is desirable to minimize its formation. Both cycles generate a significant fraction of the total N_2O emissions during the middle section of the cycle when engine load and engine-out NOx emissions are elevated compared to other portions of the cycles. These higher engine-out NOx emissions could be generating N_2O over the SCR catalyst or the ASC catalyst. For this study, emissions were measured at the engine-out and tailpipe locations, so it is not possible to see NO_2/NOx upstream of the SCR or NH_3 slip upstream of the ASC to clearly identify the primary drivers for N_2O formation. However, future work will include measurements between the emissions control system components, which will enable identification of the key mechanisms leading to N_2O formation and strategies to minimize N_2O emissions.

The differences in the two cycles were summarized above. Both cycles exhibit NOx emissions due to extended idle operation that causes a reduction in SCR temperature, and thus NOx conversion efficiency. The overall NOx conversation efficiency is shown in Figure 19 where the off-road LLAC is close to 98% while the on-road LLC is slightly below 90% due to longer operation at idle conditions. Idle operation is important for real world off-road machines and on-road driving. This should be considered when developing future engine and aftertreatment systems.

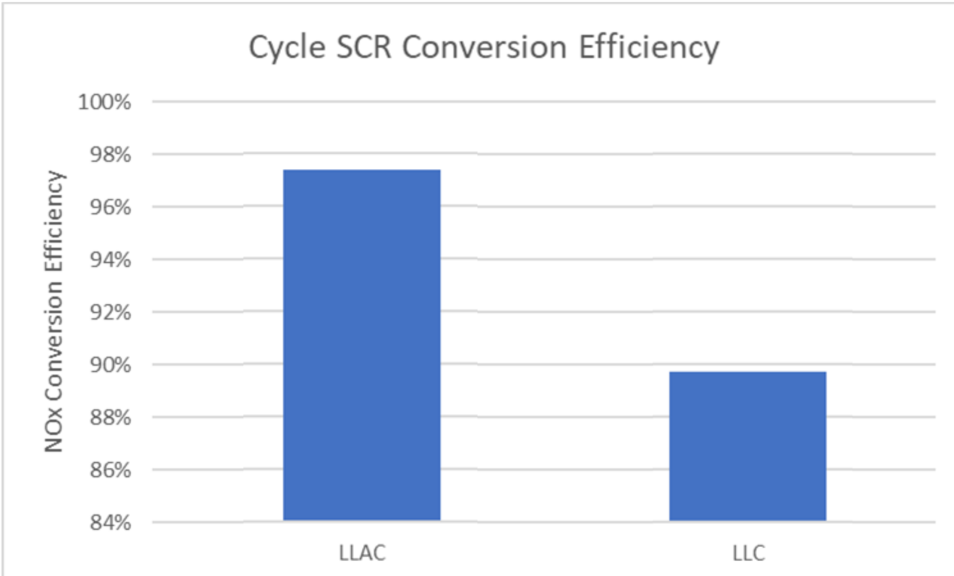


Figure 19: Overall NOx Conversion Efficiency

Summary and Conclusions

The off-road market will be adding an off-road LLAC for emissions certification in the near future. The LLAC proposed for evaluation in 2021 was evaluated in this paper relative to the on-road LLC that is currently regulated. A 13L diesel engine was used with a base calibration designed for the off-road market. This same base engine is also used for the on-road market with a different calibration; however, the off-road calibration was used in this study. Since the LLAC has not been finalized, this study is being conducted to compare and contrast the LLC for on-road with the LLAC for off-road as there might be some shared learnings.

A key observation is that the off-road LLAC includes more high load operation, which keeps the SCR temperature higher than the on-road LLC. In addition, the longest LLAC idle duration is 352 sec long, as opposed to 640 sec in the LLC, which prevents the SCR temperature from dropping as much. The LLC experiences significant NOx breakthrough with the load increases during and at the end of the long idle period from 4230 sec to 4870 sec due to the SCR temperature dropping below 200 °C.

The off-road LLAC does not experience significant NOx breakthrough as the load increases following idle periods. There is sufficient thermal inertia in the exhaust system and Tier 4 Final aftertreatment system to maintain the SCR temperature above 200 °C, which maintains NOx conversion efficiency. As this aftertreatment does not include a DPF, there is significantly lower thermal inertia in the aftertreatment system upstream of the SCR compared to an on-road aftertreatment system. The additional thermal inertia of a DPF would reduce the degree to which the SCR temperature drops during the long idle period of the LLC, which would increase the NOx conversion efficiency. Thermal inertia is an important consideration for emissions certification, which can be leveraged to avoid supplementary heating methods (such as the exhaust flap or exhaust heaters) – this system has no DPF which has pros and cons.

In summary, the off-road LLAC is a higher load cycle than the on-road LLC and results in 75% higher work, 40% more fuel, 80% lower brake specific NOx, and 18% lower brake specific CO_2. The on-road LLC is a longer cycle with more time spent at idle. Overall, the NOx conversion efficiency on the off-road LLAC was higher (almost 98% due to higher overall SCR temperatures) than the on-road LLC (about 90% due to SCR temperature dropping to 200 °C during the last idle portion). A follow-up study with a DPF would be warranted to capture the thermal inertia aspects and its effect on the downstream SCR.

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