

Meeting Nonroad Final Tier 4 Emissions on a 4045 John Deere Engine Using A Fuel Reformer and LNT System with An Optional SCR Showing Transparent Vehicle Operation, Vehicle Packaging and Compliance to End-of-Life Emissions

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ABSTRACT

The nonroad Final Tier 4 US EPA emission standards require 88% reduction in NO_x emission from the Interim Tier 4 standards. It is necessary to utilize aftertreatment technologies to achieve the required NO_x reduction. The development of a fuel reformer, lean NO_x trap (LNT) and optional selective catalytic reactor (SCR) on a John Deere 4045 nonroad engine is described in this paper. The paper discusses aftertreatment system performance, catalyst formulations and system controls of a fuel vaporizer, fuel reformer, LNT and SCR system designed to meet the nonroad Final Tier 4 emission standards. The 4045 John Deere engine was calibrated and integrated with the aftertreatment system. The system performance was characterized in an engine dynamometer performance test cell, durability test cell and on a vehicle. The catalyst performance was evaluated using aged catalysts and a detailed description of the LNT, DPF and SCR catalysts is provided. Test results show that the system performance met Final Tier 4 emission standards under a range of test conditions including limited vehicle operation.

System performance was characterized under the nonroad transient cycle (NRTC), ramped eight-mode cycle, steady state modal points and not-to-exceed regulations. LNT regeneration, LNT desulfation and DPF regeneration were demonstrated in these test cycles while maintaining repeatable and consistent aftertreatment temperature control. The LNT system regeneration fuel consumption ranged between 1.4% to 3.1%. The system consistently demonstrated 85% NO_x reduction in a performance and durability test cell, and on a vehicle. The downstream SCR catalyst can be removed as an option for tighter vehicle packages while still meeting Final Tier 4 emission standards.

I. INTRODUCTION

The Environmental Protection Agency (EPA) issued emission legislation for diesel engine vehicles. EPA Final Tier 4 emission regulations are required for nonroad vehicles in 2014 and 2015 depending on specific engine power levels. The fuel reformer and lean NO_x trap (LNT) system has been considered for meeting Final Tier 4 nonroad emission standards as part of the technology evaluation and

development programs at John Deere. This system provides a cost-effective technology option that does not require an additional fluid to meet the stringent NO_x emissions standards. The 4045 John Deere 4.5 L engine was chosen to evaluate the fuel reformer-LNT technology.

The objective of the work in this paper was to demonstrate Final Tier 4 emissions compliance on a John Deere 4045 engine using both aftertreatment systems in [Figures 1a](#) and [1b](#). The engine had three power calibrations including 104 kW, 85 kW and 78 kW. Dynamometer test results are reported over key individual operating modes such as the 8-mode test cycle, nonroad transient cycle (NRTC) and ramped 8-mode cycle. The key operating modes for the aftertreatment system were demonstrated on these cycles which include LNT regeneration, DPF regeneration and LNT desulfation.

The feasibility of a fuel reformer, LNT and selective catalytic reduction (SCR) aftertreatment system to meet Final Tier 4 nonroad emissions standard of 0.4 g/kW-hr NO_x has been addressed [[1](#), [2](#), [3](#)]. The paper describes the development of a nonroad John Deere 4045 engine with a fuel reformer LNT system meeting Final Tier 4 emission standards. Similar systems have been shown to meet heavy and medium duty EPA 2010 on-highway emissions standards [[4](#), [5](#)]. This paper also provides an overview of tests conducted to meet Final Tier 4 emission levels followed by detailed descriptions of the engine calibration, control system, catalyst formulation, vehicle packaging, vehicle demonstrations and end-of-life durability testing.

The aftertreatment system consists of a fuel dosing system, mixing elements, fuel vaporizer[6], fuel reformer, LNT, diesel particulate filter (DPF), and SCR catalyst arranged in series. A sample configuration of this system is shown in [Figure 1](#). Similar systems using LNT and SCR technology without a fuel reformer are cited in literature [[7](#), [8](#), [9](#)]. A fuel reformer is utilized to generate hydrogen (H₂) and carbon monoxide (CO) using diesel fuel. These reductants are used to regenerate and desulfate the LNT catalyst. NO_x emissions are reduced using the combination of the LNT and SCR catalysts. During LNT regeneration, ammonia (NH₃) is intentionally released from the LNT and stored on the downstream SCR catalyst to further reduce NO_x that passed through the LNT catalyst. This approach converts the drawbacks of the single leg LNT approach (low conversion during regeneration and NH₃ slip) into an advantage while remaining independent of any urea infrastructure since diesel fuel is the only reductant [[1](#), [4](#), [5](#), [7](#), [10](#), [11](#), [12](#), [13](#), [14](#), [15](#)]. The DPF is regenerated using the fuel reformer similar to diesel oxidation catalyst (DOC) by injecting fuel under lean exhaust operating conditions. [Figure 1](#) shows two configurations of the aftertreatment system with and without the optional SCR. The packaging option without the SCR

provides an added benefit to nonroad vehicles with limited packaging space.

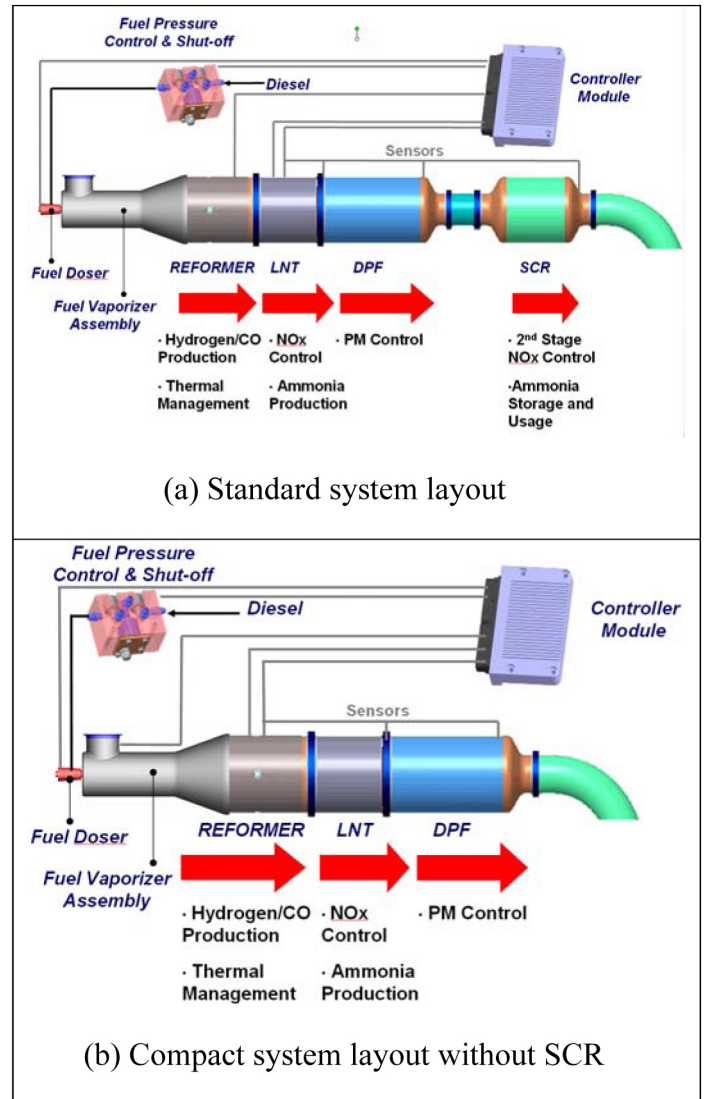


Figure 1. Aftertreatment system layout (a) with SCR and (b) without SCR

Aftertreatment catalyst technology is constantly being improved. Improvements include catalyst performance and cost by the reduction of precious group metals (PGM). The key precious group metals are platinum (Pt), palladium (Pd) and rhodium (Rh). The catalysts in this system all represent improvements in cost and performance over previous similar systems [[1](#)]. The PGM cost of both the LNT and the DPF in this project was reduced over previous systems. The total mass of PGM was reduced by replacing more expensive Pt and Rh (LNT only) with Pd.

The aftertreatment system provides a vehicle solution that remains transparent to vehicle operators. The system uses diesel fuel to regenerate the LNT catalyst, thus eliminating

the need for an additional fluid such as urea. Additionally, the fuel dosing system [16] uses fuel to cool the injector such that separate coolant lines are not required. The system and its catalysts have proven to be durable and robust [1, 3, 10] while demonstrating a significant achievement in end-of-life emission reduction requirements. The system is attractive for space constrained vehicles because of its compact packaging size. [Figure 2](#) shows the system set up in a test cell that packages more efficiently than urea-SCR systems with a DPF. A urea-SCR system will require additional space for urea heated lines, additional urea hydrolysis mixing length, an additional doser for hydrocarbon dosing and a urea tank. Additionally, the cost of the systems in [Figure 1](#) have shown to be competitive, and in many instances, less than urea-SCR systems with a DOC and a DPF.



Figure 2. Engine and Aftertreatment System in a Test Cell

Aftertreatment system packaging was very important in this study. Three configurations were explored. The base configuration included the full system shown in [Figure 1a](#) that included the fuel vaporizer, fuel reformer, thermal mass, LNT, DPF and SCR. A more compact system was verified and shown in [Figure 1b](#) that included a slightly larger LNT without the optional SCR. The last configuration included a variation of [Figure 1b](#) by replacing the thermal mass with the DPF. The DPF in this configuration serves as a thermal mass in front of the LNT to absorb the heat generated by the fuel reformer during a LNT regeneration. The LNT remains at its ideal temperature for NOx reduction by using the thermal mass or the DPF as a heat sink. This configuration was not demonstrated as part of this work; however, packaging options using this configuration are presented.

II. SYSTEM SIZING AND PACKAGING

Aftertreatment system sizing was performed for two vehicle applications having multiple variations in aftertreatment components. The base configuration included the aftertreatment configuration from [Figure 1a](#) and was packaged on a John Deere 410J vehicle. This system consisted of a fuel vaporizer, fuel reformer, thermal mass, LNT, DPF and SCR. This system was tested in a dynamometer lab to validate emissions compliance [2] and was used for the vehicle demonstration. Variations of the aftertreatment system without the SCR catalyst are feasible [2]. A second packaging study was performed on a John Deere Series 5000 vehicle.

The aftertreatment system was sized to meet the 104 kW power rating of the John Deere 4045 diesel engine that had an engine displacement of 4.5 liters. The base configuration system required the catalyst sizes shown in [Table 1](#). The fuel vaporizer was sized at 4 inches in diameter by 3 inches in length. The fuel reformer was sized at 7.48 inches in diameter by 5.12 inches in length. The thermal mass was sized at 9.06 inches in diameter by 2.93 inches long such that it had similar volume as the fuel reformer. The thermal mass closely matched the diameter of the LNT. The LNT and SCR catalysts had equivalent sizes at 9 inches in diameter by 6 inches in length. The DPF was sized similar to interim Tier 4 sizes at 9 inches in diameter by 8 inches in length. The same size catalysts were used for the 78 kW vehicle and test cell demonstrations; however, smaller catalysts are possible for this power rating.

Table 1. Catalyst Sizes

	Reformer-Thermal Mass-LNT-DPF-SCR			Reformer-Thermal Mass-LNT-DPF		
	104kW		78kW	104kW	85kW	78kW
EFV	4" x 3"			4" x 3"		
Fuel Reformer	7.48" x 5.12"			7.48" x 5.12"		
Thermal Mass	9.06" x 2.93"			9.06" x 2.93"		
LNT	9" x 6"			9" x 8"		
DPF	9" x 8"			9" x 8"		
SCR	9" x 6"			none		

There are additional packaging variations that can be considered for vehicle installations. [Table 1](#) also shows the system sizing for three engine power ratings with the SCR removed. The same size fuel vaporizer, fuel reformer, thermal mass and DPF sizes remain the same as the base configuration. The LNT was made slightly larger by adding another 2 inches to the length of the substrate to compensate for the NOx that would be removed by the SCR. This same set of hardware was used for engine power ratings of 104 kW, 85 kW and 78 kW. Smaller catalysts could be used for cost reduction for the lower power ratings if parts commonality across engine power ratings was not a concern.

The John Deere 410J backhoe loader was chosen for the vehicle demonstration program to evaluate the aftertreatment

system package size within the space constraints of the vehicle. The base aftertreatment system configuration that was packaged inside the existing 410J vehicle is shown in [Figure 3](#). Exhaust enters the aftertreatment system from the turbocharger and proceeds into the fuel vaporizer assembly. Fuel is periodically injected into the fuel vaporizer to vaporize the fuel [6]. The exhaust and fuel vapor mixture travels through a one-hundred eighty degree bend into the fuel reformer catalyst in order to facilitate compact vehicle packaging. Fuel vapor mixing simulations were conducted to ensure complete fuel and flow uniformity entering the fuel reformer similar to previous works [17]. The exhaust proceeds through the thermal mass, which is used to absorb the heat wave generated by the reformer from the downstream LNT catalyst. The exhaust exits the LNT and enters the DPF. An air ejector is placed between the DPF and SCR to passively induce ambient air to cool the exhaust stream, while maintaining a fuel-lean mixture entering the SCR [2]. Finally, the SCR catalyst is used as a clean up catalyst for the remaining NO_x, hydrocarbon and in the case of desulfation, conversion of hydrogen sulfide (H₂S) to sulfur dioxide (SO₂).

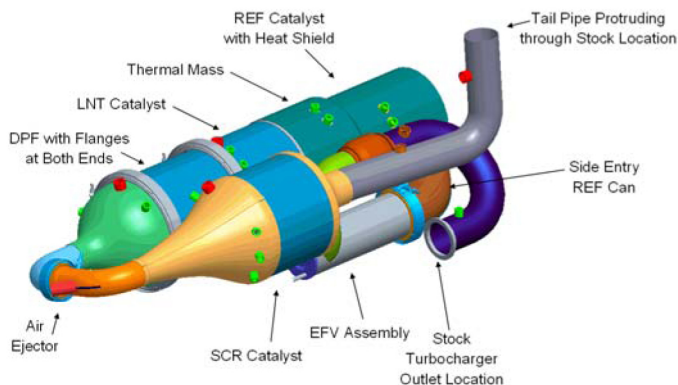


Figure 3. Base aftertreatment configuration

[Figure 4](#) shows the installation of the base aftertreatment configuration in the 410J vehicle. The 410J vehicle had an engine power rating of 78 kW while the base aftertreatment system was built for a 104 kW engine. As a result, this larger system was used to demonstrate two purposes; parts commonality in testing and ease of packaging. The aftertreatment system was positioned on the top of the engine and below the vehicle hood. The aftertreatment system connects directly to turbocharger and has the same layout as shown in [Figure 3](#). Likewise, the system accommodates the existing tailpipe location on the vehicle. An auxiliary fuel pump was added for the vehicle demonstration; however, the product vision is to integrate the aftertreatment fuel doser into the existing engine fuel pump. The air ejector was positioned near the front of the vehicle and solutions for eliminating ambient debris from the induced ambient air were proposed. Subsequent testing [2] showed that the SCR could be

removed from the system, which also removes the ejector and the need for a debris elimination solution. The catalyst layout in [Figure 4a](#) was used for all testing with and without the SCR. The system shown in [Figure 4b](#) was used for the vehicle demonstration.

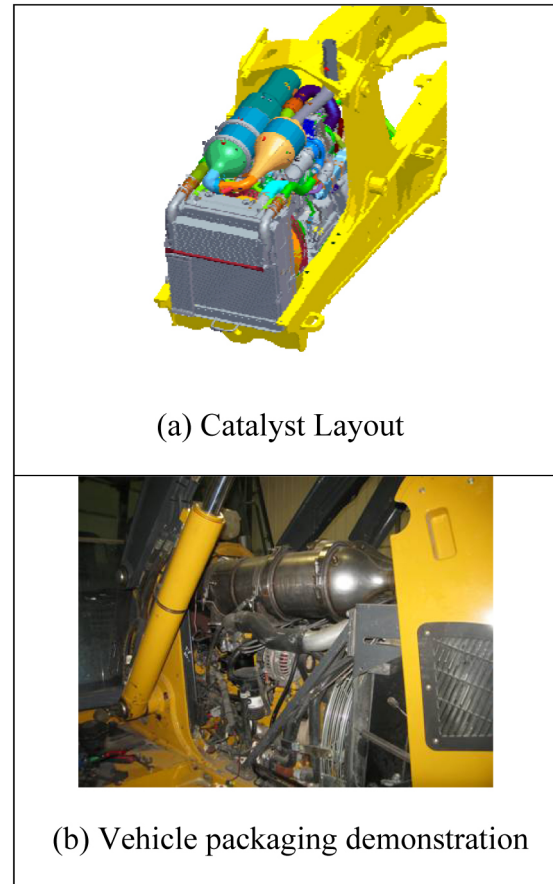
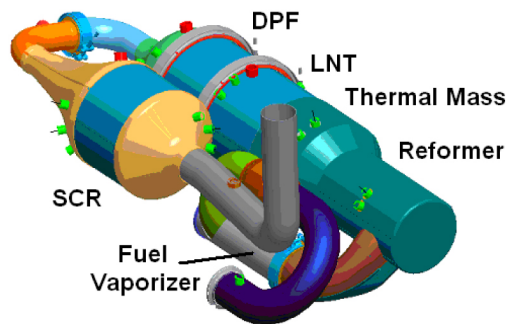
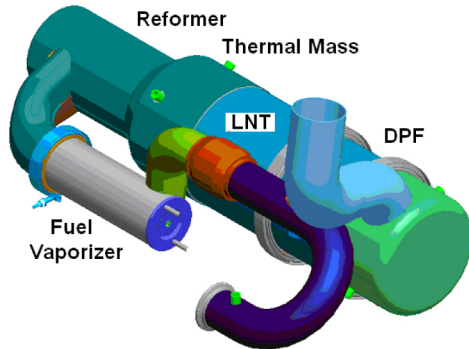


Figure 4. 410J (a) Catalyst Layout and (b) Vehicle Packaging Demonstration

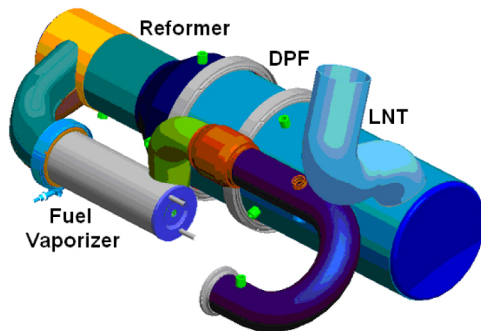
[Figure 5](#) shows the vehicle layout options for the base configuration without the SCR and a system without the thermal mass to further reduce package size. The base configuration in [Figure 5a](#) is provided for reference. The system without the SCR in [Figure 5b](#) offers more room to package auxiliary components in the vehicle. It also offers more packaging options since this configuration does not consume the entire free space above the engine. Finally, a system shown in [Figure 5c](#) is proposed to eliminate the thermal mass by placing the DPF between the fuel reformer and the LNT. The DPF has enough thermal capacity to replace the metal monolith thermal mass; thus, providing a lower cost system that uses less space. This system is currently under investigation while test results meeting Final Tier 4 were achieved for the other two systems [2].



(a). Reformer-Thermal Mass-LNT-DPF-SCR



(b). Reformer-Thermal Mass-LNT-DPF



(c). Reformer-DPF-LNT

Figure 5. System Packaging Alternatives

The packaging of the aftertreatment system and cost are critical challenges facing the Final Tier 4 compliant 5000 series tractors. Figure 6 shows the vehicle package with the aftertreatment system positioned under the vehicle hood.

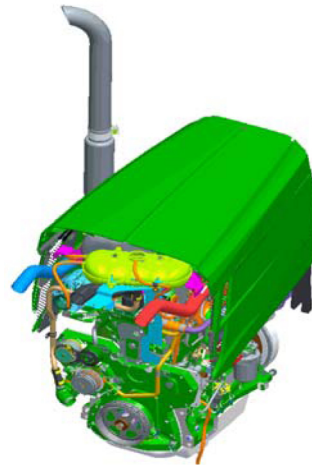


Figure 6. Concept design of a 5000 series tractor with a 4045 engine and fuel reformer, LNT and DPF system

A packaging study was performed on the John Deere Series 5000 vehicle platform similar to that performed on the John Deere 410J vehicle. The objective of this packaging exercise was to show that the aftertreatment system fits into the vehicle using the system without the SCR shown in Figure 5b; however, fuel and exhaust flow simulations were not performed for this configuration. Figure 7 shows the packaging on the Series 5000 vehicle, which has similarities to the 410J packaging. This configuration positions the fuel vaporizer directly upstream of the fuel reformer catalyst. This configuration is anticipated to perform well due to a lack of exhaust pipe bends between the fuel vaporizer and reformer, enhancing exhaust flow uniformity entering the reformer. An additional change to the configuration is the thermal mass, which is positioned in a bend between the fuel reformer and the LNT. Since the thermal mass is a metal monolith designed to adsorb the heat wave from the fuel reformer to the LNT, the design objective is to optimize flow into the LNT which has been shown on similar packages in previous work [17].

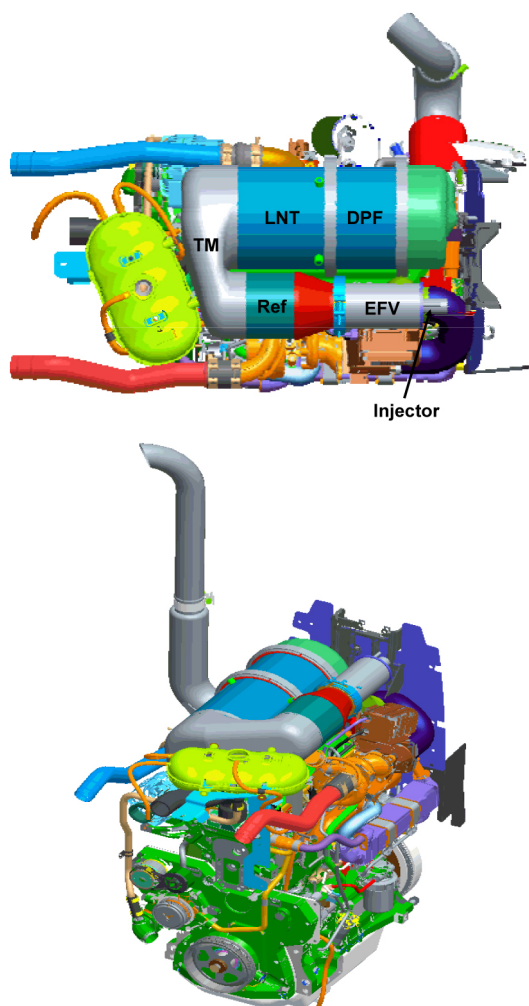


Figure 7. Aftertreatment Packaging on a John Deere Series 5000 Engine

III. SYSTEM OPERATION

The three main modes of operation for the aftertreatment system include LNT regeneration, LNT desulfation and DPF regeneration. All modes of operation require injecting diesel fuel into the fuel reformer catalyst to produce the appropriate reductant. The reformer operation will be described followed by the three main modes of operation.

The fuel reformer is operated in both lean and rich modes to provide a means to regenerate the LNT and DPF in the aftertreatment system. Its two main functions during LNT regenerations are 1) to consume the residual oxygen (O_2) in the exhaust gas stream, and 2) to convert remaining reformer fuel to the reductants, H_2 and CO [1, 5, 6, 7, 8, 9, 10, 11, 12]. A typical reformer control during LNT regeneration is shown in Figure 8. Fuel is injected into the reformer to warm the catalyst to its operating temperature. Engine out O_2 is then reduced via engine control to a lower level (i.e., 4.3% in the example). A higher fueling rate is commanded to consume

enough oxygen to reach a rich condition as depicted by the tailpipe O_2 dropping lower to 1%. The higher fuel rate creates a rich condition where reformate is produced, as depicted by the predicted CO and H_2 profiles. This next section will discuss the engine calibration to reduce engine out O_2 level required by the reformer.

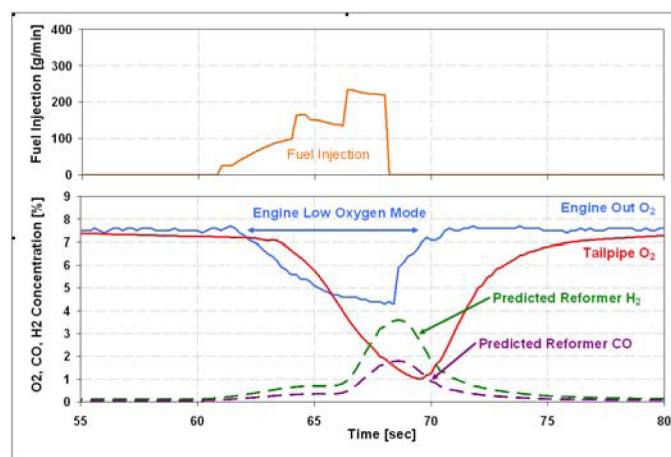


Figure 8. Typical reformer operation

A 4045 John Deere engine with a variable geometry turbine (VGT) turbocharger, high pressure loop exhaust gas recirculation (EGR), common-rail fuel injection system and air throttle was used in this study. The air throttle was mainly used for low O_2 mode control as shown in Figure 8. The engine controller was modified to communicate with the aftertreatment system. The engine controller communications with the aftertreatment controller is simple. The engine controller provided engine speed, load and exhaust flow rate for the aftertreatment system controller and received a low O_2 request flag from the aftertreatment controller. The low O_2 request flag is sent from the aftertreatment controller to the engine controller to switch from normal to low O_2 mode when a LNT regeneration or desulfation is needed.

Aftertreatment performance was characterized at Modes 1-3 and 5-7. The engine was allowed to stabilize prior to running each modal point. The exhaust flow rate, turbocharger exit temperature and engine out NOx are key parameters to monitor for stability prior to LNT regeneration. The average turbocharger exit temperature for this data set was $464^{\circ}C$ including normal and low O_2 mode operation. Multiple regenerations were required to allow the LNT regeneration performance to stabilize. The first LNT regeneration was removed from the cycle calculations. In the baseline configuration, an air ejector was used to lower the SCR inlet temperature. As a result, the SCR outlet measurements were corrected for the additional induced ambient air. Figure 9 shows a LNT regeneration at Mode 5. The colors of the bars correspond to the lines on the chart. Engine out NOx is red.