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IMPACT OF HYDROGEN-DIESEL DUAL FUEL COMBUSTION ON THE PERFORMANCE OF AFTERTREATMENT SYSTEM IN HEAVY DUTY COMMERCIAL TRUCK

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Abstract**—** Hydrogen has emerged as a promising near-term solution for enhancing the performance of internal combustion engines. Hydrogen-diesel dual fuel (H_2-DF), where hydrogen is introduced in the intake of a heavy-duty diesel engine, reduces tailpipe CO_2 emissions but also impacts other pollutants. This study investigates the correlation between the hydrogen addition to diesel engines and the effectiveness of exhaust aftertreatment systems (EATS) in reducing emissions. H_2-DF combustion impacts the temperature and composition of the exhaust gas, which may impact the performance of EATS. To evaluate the performance of EATS components, analysis of emission data measured using a class-8 commercial truck operated on a chassis dynamometer at steady state conditions is conducted. Conventional diesel and H_2-DF operation are compared at 1200 RPM and 200 Nm shaft torque. Engine-out emissions, NOx conversion rate, and temperatures at key points in the EATS are compared. The time for the EATS components to reach stable temperatures depended on the prior operating condition. In H_2-DF, a significant increase in temperature across the catalyst system was observed compared to diesel, resulting in an increase in NOx conversion rates. In H2-DF, engine-out NOx emissions were comparable to conventional diesel while CO and CO_2 were reduced. A sensitivity analysis of diesel-based SCR with the computational tool GT-SUITE was also performed, which indicated SCR temperature and NH_3 dosing have significant impact on the performance of EATS.

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION

Diesel engines used in commercial trucking are one of the largest emissions sources from the transportation sector [1]. They emit pollutants including oxides of nitrogen (NOx) and particulate matter (PM) and greenhouse gases (GHGs) [2]. NOx have harmful effects on the environment and human health [3], and are facing increasingly stringent regulatory requirements for emissions control. To cope with current and future regulations, modern diesel engines are equipped with an exhaust aftertreatment system (EATS) with multiple catalytic components to treat the different pollutants in the exhaust [4]. Adding hydrogen to the intake air in a diesel engine can reduce tailpipe CO_2 emissions, but its impact on the performance of the EATS needs to be investigated.

Typical heavy-duty diesel engine EATS consists of a Diesel oxidation catalyst (DOC), a Diesel Particulate Filter (DPF), and a Selective Catalytic Reducer (SCR), as shown in Fig.1. The DOC oxidizes unreacted HC and CO into CO_2, while the DPF removes PM, including soot. The SCR converts NOx into N_2: to achieve this reduction reaction in an oxygen-rich environment requires the addition of a reducing agent: Diesel Exhaust Fluid (DEF), a urea solution [5]. DEF is dosed at the upstream of SCR where it gets mixed with exhaust gas as depicted in the Fig.1.

The performance of EATS components is dependent on catalyst type and size and various operational factors, including exhaust gas composition, temperature variations, and space velocity, which can affect their efficiency. These factors influence the removal of pollutants due to chemical reactions taking place inside the individual EATS components.

A hydrogen-diesel dual fuel engine (H_2-DF) engine involves injecting hydrogen upstream of the intake manifold, where it mixes with air before entering the engine cylinder, followed by the combustion of the air-gas mixture initiated by the diesel injection [6]. Hydrogen addition into the diesel engine may result in some unreacted hydrogen (hydrogen slip) in the exhaust gas as well as different compositions of exhaust gas due to its variations in the combustion process. The addition of hydrogen to diesel engines introduces unique dynamics that could impact the performance of EATS system. It changes the thermal conditions and the chemical reactions inside the system.

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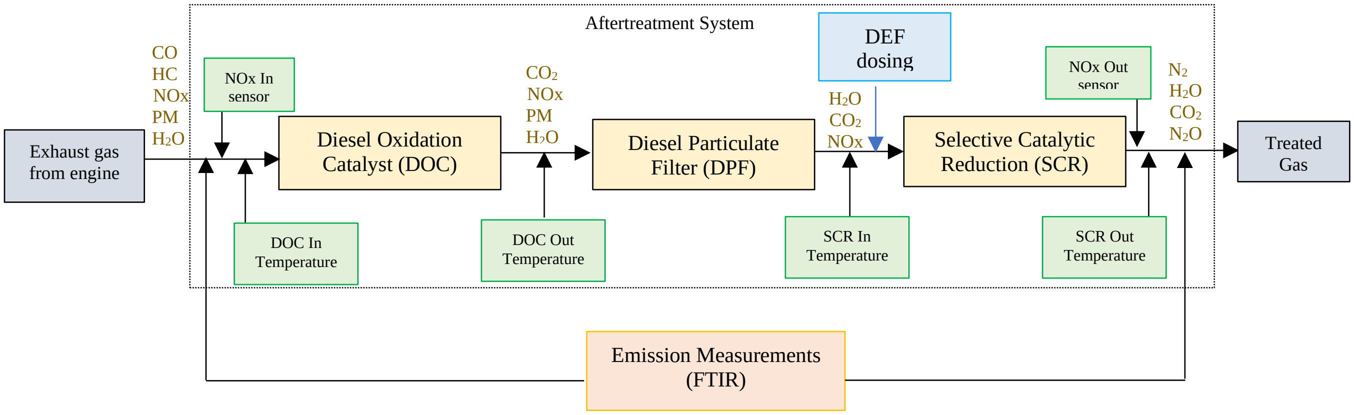


Figure 1: Block diagram of Aftertreatment system

The presence of H_2 has been shown to enhance the performance of the DOC by promoting the oxidation of CO and HC [7]. H_2 also helps to oxidize NO into NO_2 in the DOC, improving the performance of SCR as well. In the SCR, NO and NO_2 react with NH_3 from the DEF. The SCR reactions that involve both NO and NO_2 is faster; thus, the rate of NOx reduction is higher in case of a higher NO_2/NOx ratio. In SCR, H_2 helps to reduce NOx and improve its performance [8] [9]. Any H_2 present in the SCR would act as the reducing agent and react with NOx. However, it is likely that most H_2 in the exhaust will have been oxidized in the DOC (see Fig. 1) and so would not reach the SCR.

The objective of this study is to understand the impact of H_2-DF on the EATS of a heavy-duty commercial truck, including the temperature of the primary EATS components and the NOx conversion rate. The analysis is based on chassis-dynamometer data combined with a simplified SCR model to assess sensitivity of the of H_2-DF SCR at a low-load operating condition.

II. METHODOLOGY

Hydra Energy has developed a H_2-diesel dual fuel dosing system for class-8 commercial heavy-duty trucks. The H_2-DF system performance was assessed by running a commercial heavy-duty truck on a chassis dynamometer in both diesel and H_2-DF modes under steady-state conditions [6]. Specifications for the vehicle, engine and aftertreatments system are provided in Table 1. Emissions were measured using a Fourier transform infrared (FTIR) system (Bruker MATRIX MG5), configured to measure from either upstream or downstream of the aftertreatment system. Onboard OEM NOx sensors, located before the DOC and after the SCR, provided simultaneous measurements to supplement the FTIR. Temperatures through the aftertreatment components were also monitored using on-vehicle sensors. Reference [6] provides more information on the instrumentation and data acquisition procedures. The purpose of this study was to compare the emissions produced by the engine and the performance of EATS both for diesel and H_2-DF engine.

TABLE 1: SPECIFICATIONS OF HEAVY-DUTY COMMERCIAL TRUCK

Vehicle model	2016 Freightliner CA125DC
Engine model	Detroit Diesel DD15
Emission certification	GHG14, EPA2010
H_2-DF system	Hydra Energy Co-combustion
Aftertreatment system	DOC + DPF + SCR
No. of Cylinders	6
Displacement (L)	14.8

EATS temperatures were evaluated for investigation of their stabilization phase. The stabilization criteria for EATS components used in this study is characterized by minimal temperature fluctuations and a consistent temperature gradient across the component. For SCR, when its inlet temperature stabilizes and differential across the component is within 10ºC, this condition is also considered as stable for this study. Stabilization time of these components is also dependent on the previous condition of engine and EATS. The prior condition of this test point for diesel fuel was H_2-DF operation at 14% engine load while for H_2-DF test point, engine was operating with H_2-DF with varying engine load under 25%.

The H_2-DF condition was achieved by adding H_2 and reducing the engine demand torque correspondingly to maintain a constant output shaft torque. The data point used for this paper was taken at engine speed of 1200 RPM and 200 Nm of shaft torque both for diesel and H_2-dual fuel. This point was chosen due to the higher complexity of the EATS performance at low engine load, due to low temperatures and flow rates. Along with experimental work, study through modelling is also carried out.

To supplement the experimental results, an SCR model for a diesel engine was developed in GT-SUITE, informed by literature data and emissions measurements. SCR modelling requires reaction kinetics as well as operating parameters. The most important component of SCR is the catalyst that promotes NOx reduction. As the catalyst type and Platinum Group Metals (PGM) loading are unknown for the EATS used in the experimental tests, this data is taken from the literature [10]. Cu-Zeolite is used as the catalyst material in this model. The rate of reactions and activation energies, along with the chemical reactions, are also used from the same reference. The physical properties of the exhaust gas including composition, and temperature were matched to the engine experimental data. The simulated mass flowrate was scaled relative to the tested engine system to match SCR space velocity.

A sensitivity analysis of this model was performed for parameters including SCR temperature, DEF dosing, NO/NO_2 ratio and space velocity. The sensitivity analysis highlighted important parameters that are required for the modeling of SCR for H_2-DF engines.

III. RESULTS AND DISCUSSION

A. *Experimental Data Analysis*

Experimental measured data from H_2-DF engine was analyzed for emissions as well as the temperature of EATS. The results for emissions and temperatures are discussed separately below:

Temperatures:

The thermal profiles of EATS vary across components due to their distinct operational roles, such as oxidation and reduction reactions, and are influenced by the operating condition and whether H_2-DF or conventional diesel operation. Each component needs a specific stabilization time to give its optimal performance, with the overall aftertreatment system achieving stability subsequent to the stabilization of engine parameters. During the stabilization phase, the performance of these components is unpredictable due to ongoing chemical reactions influenced by multiple factors.

The stabilization duration differs among components; for instance, the DOC typically stabilizes within 5 minutes. Being further downstream, the inlet conditions to the SCR do not stabilize until the DOC and DPF have reached constant temperatures. Furthermore, the active control over DEF dosing, the storage of ammonia on the catalytic sites, and the complex reduction-reaction chemistry lead to stabilization periods of 8 to 10 minutes for the tested conditions.

The aftertreatment system takes several minutes to reach stable temperatures after the engine operation stabilizes, as illustrated in Fig. 2 & 3. The time series in the figures start when engine operation was stable, defined by constant intake air flow rate, intake and engine exhaust system temperatures and pressures, and constant output torque. In the diesel scenario (Fig. 2), the DOC temperature stabilizes after 75 seconds, while the SCR inlet and outlet temperatures initially decline before reaching the stabilization point (at 340 seconds). Conversely, in the hydrogen-diesel dual-fuel (H_2-DF) case (Fig. 3), both DOC and SCR inlet and outlet temperatures rise initially and then stabilize. DOC became stable at 240 seconds, while SCR stabilized at 420 seconds. These differences are primarily a function of the historical condition of the EATS based on the preceding test points.

Stabilization Phase:

During unstable EATS conditions, the SCR inlet temperature slightly exceeds the DOC outlet temperature for diesel-only operation. In contrast, for H_2-DF, a temperature drop is observed between the DOC outlet and SCR inlet, suggesting an impact of hydrogen on Diesel Particulate Filter (DPF) operation. Additionally, in the H_2-DF scenario, the SCR outlet temperature is lower than its inlet temperature, whereas, for diesel, the SCR outlet temperature surpasses the inlet temperature. This difference is more prominent in unstable conditions but becomes negligible as the system stabilizes. This suggests that the reaction kinetics inside the SCR are changed, affecting the thermal conditions. Understanding these thermal behaviors is crucial for optimizing the performance and efficiency of aftertreatment systems in varying fuel contexts.

Stable Condition:

The temperature outlet from the DOC is significantly higher in the case of H_2-DF than for conventional diesel. As the DOC inlet temperature for both fuels is almost the same and follows the exhaust gas temperature trend, there is a significant rise in temperature in H_2-DF in the DOC. This is likely due to the exothermic oxidation reaction of unreacted H_2. This high temperature in the DOC outlet results in higher temperatures in the DPF (Fig. 1) and at the inlet to the SCR (Fig 2 & 3). The temperature change across the SCR is small in stable conditions for both diesel and H_2-DF cases.

Emissions:

The emissions formed from diesel fuel combustion include CO_2, CO, NOx (NO and NO_2), H_2O molecules and unreacted Hydrocarbons (HC). In the H_2-DF case, there would be some hydrogen in the exhaust gas. The time series data of onboard NOx sensors measuring concentrations at both the inlet and outlet of the EATS for diesel and H_2-DF operations is shown in Fig. 2 & 3, respectively. These values were compared with the data measured using FTIR and found to be very close to FTIR values, as shown in Fig. 3.

The average engine out emissions entering the EATS are different for diesel and H_2-DF, as shown in Fig. 4. Once the engine operation stabilized, these concentrations were constant throughout the testing, including EATS stabilization phase and steady-state phases. Engine-out emissions of CO and CO_2 were higher for diesel than for H_2-DF. For the same reason, H_2O content increases in H_2-DF. Engine-out NOx emissions, both for the H_2-DF and diesel cases, remained relatively stable throughout the test and are comparable at this operating point at approximately 200 ppm.

Stabilization Phase:

For diesel only operation, SCR-out NO_x emissions increase initially (Fig. 2 (bottom)). This correlates with a decrease in SCR outlet temperature (Fig. 2 (top). This demonstrates the SCR performance's dependence on system temperatures that respond relatively slowly to changes in exhaust stream conditions. Initially, the SCR-out temperature was higher due to the previous condition and test point, then due to a change in the test point and inlet conditions, both SCR inlet and outlet temperature started decreasing. This results in a reduction in SCR performance as well as further reduced SCR out temperature, thus increasing the $NOx_{\text{-out}}$ emissions at 150 seconds while the $NOx_{\text{-in}}$ was almost constant. After ~300 s, the SCR performance stabilized at approximately 85-90% conversion. This relatively low value is a direct result of the low temperature in the SCR (~250ºC).

For the H_2-DF case, $NOx_{\text{-out}}$ initially increased, corresponding to a reduction in SCR inlet and outlet temperature

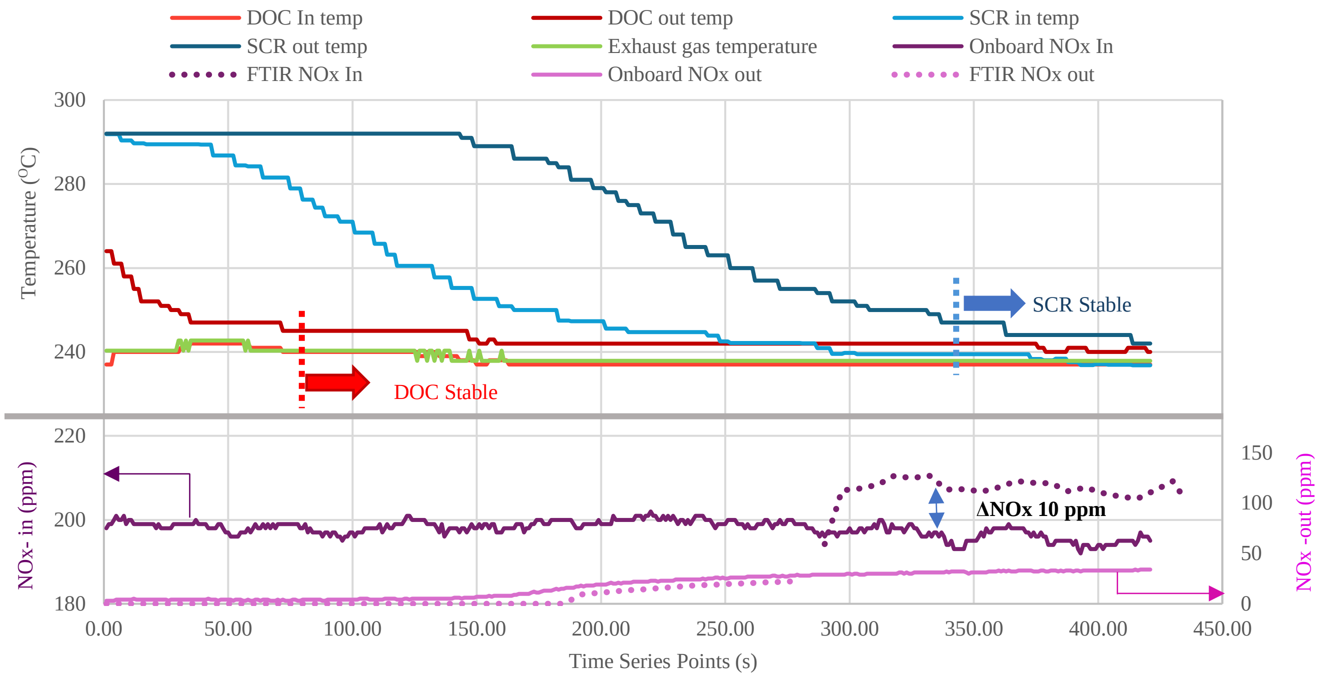


Figure 2: Time series data of DOC and SCR temperature, onboard NOx sensors and FTIR NOx for Diesel-only operation during EATS stabilization phase at 1200 RPM, 200 Nm shaft torque and an exhaust mass flowrate of 430 kg/hr.

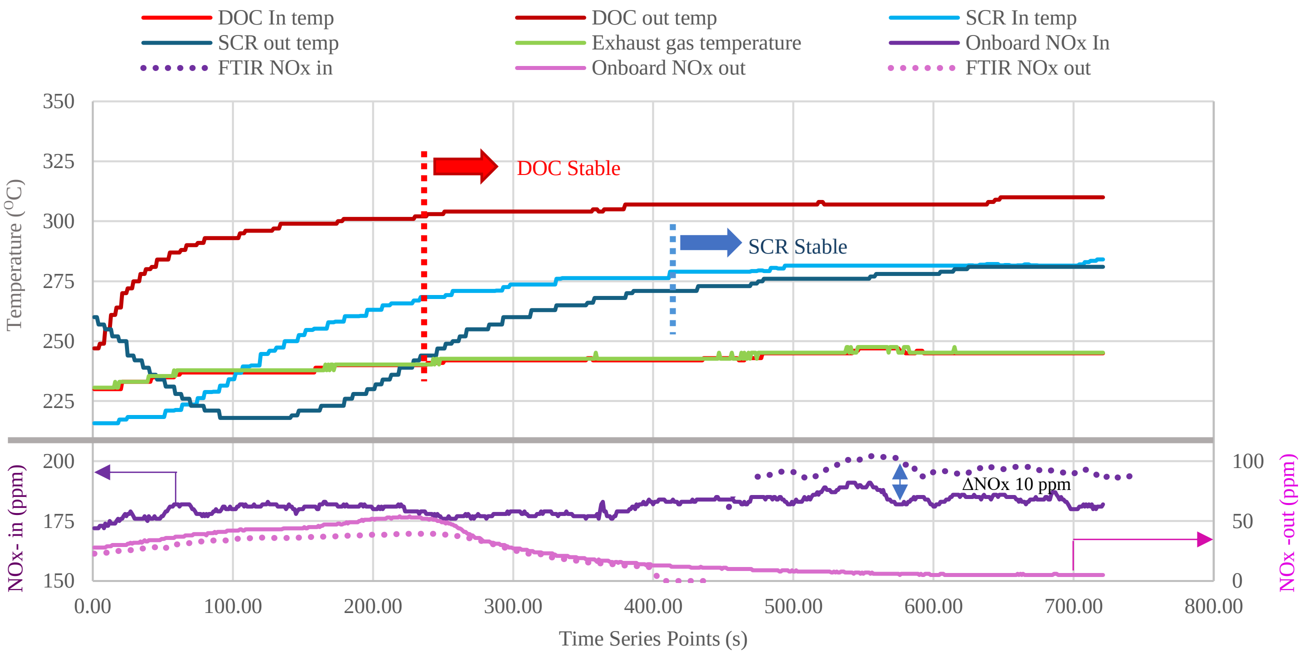
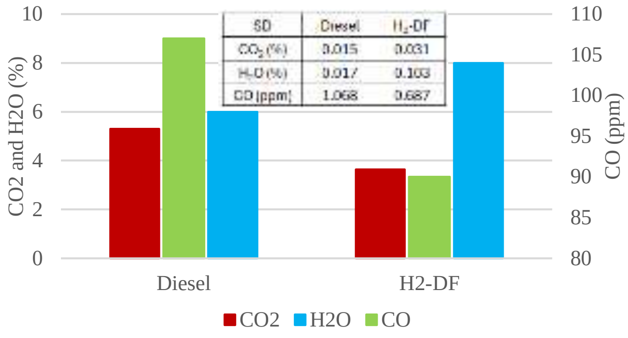


Figure 3: Time series data of DOC and SCR temperature, onboard NOx sensors and FTIR NOx for H2-DF operation during EATS stabilization phase at 1200 RPM, 200 Nm shaft torque and an exhaust mass flowrate of 470 kg/hr.

(Fig 3). The increase in DOC outlet temperature, attributed to the oxidation of H_2 in the H_2-DF case, increases the temperatures in the subsequent components. The time delay between the high DOC outlet temperature (~100s) and the SCR inlet temperature (~250 s) is due to the time needed to increase the temperature in the DPF (see Fig. 1). Once the higher temperature from the DOC propagates to the SCR, the performance increases significantly, at ~ 280 seconds.

Notably, when SCR is unstable with low temperatures, overall NO_x emissions downstream of the SCR are slightly higher for H_2-DF compared to diesel, despite overall very similar inlet NOx concentrations. It is possible that the increased



SD	Diesel	H_2-DF
CO_2 (%)	0.015	0.031
H_2O (%)	0.017	0.103
CO (ppm)	1.068	0.687

Figure 4: Pre-aftertreatment emissions for Diesel and H_2-DF at 1200 RPM and 200 Nm shaft torque

moisture content associated with H_2-DF combustion may adversely affect SCR catalyst performance, leading to reduced NO_x conversion efficiency at lower loads. [11] [12] This can be offset by higher temperatures from oxidation of H_2 in the DOC, but this depends on the stabilization phase which appears to be longer in H_2-DF as compared to diesel for this operating point.

Stable condition:

The SCR showed high NOx conversion during its stable condition for both diesel and H_2-DF operation, but the overall NOx conversion efficiency (DeNOx) was higher for H_2-DF as compared to diesel fuel as shown in Fig. 5. H_2 oxidation in the DOC increases the DOC outlet temperature, increasing the SCR inlet temperature. If any H_2 is left after passing through the DOC and DPF, it will likely participate in the NOx reduction reactions – which could further increase NOx reduction rates. [8] [9]

Other than these emissions, the NO and NO_2 ratio also differs for both fuels, as indicated in Fig. 5. The average NOx-$_{in}$ (NO and NO_2) for both stable and unstable phases are used for the comparison. Engine-out, NO is about 80% of total NO_x for diesel, while for H_2-DF, it is only ~40% of the total. Other studies also showed the same observation about NO and NO_2 ratio at low loads, but this difference becomes less prominent at higher load. [6] Post-EATS NOx is almost entirely NO_2 based on the FTIR results collected during the stabilization phase; This may be due to the limitation of FTIR for detecting NO below a certain threshold. The actual concentration values shown in Fig. 5 for NOx-$_{out}$ are from the on-board sensor values during the stable operating phase only.

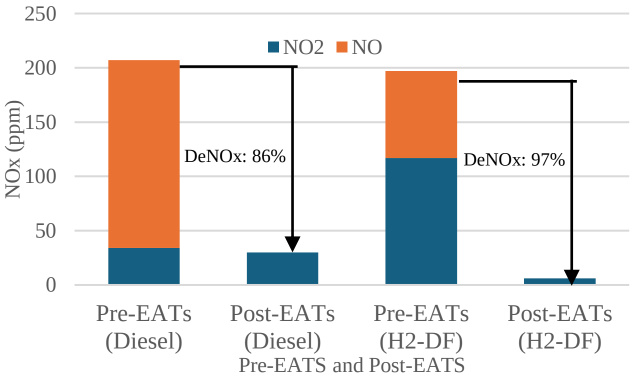


Figure 5: Engine-out (pre-EATS) NO2/NO breakdown from FTIR recorded while engine operation was stable, and NOx out from on-board sensors during SCR stable phase (shown on Figure 2 & 3).

B. *Sensitivity Analysis*

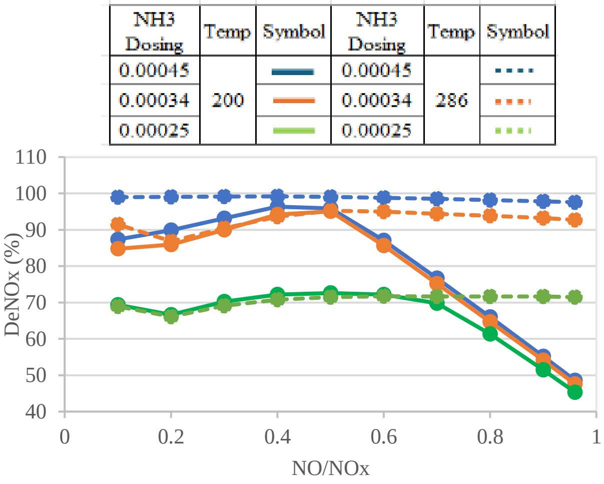
Predictive modeling of EATS components, particularly the SCR system, provides additional insight for this assessment. This model requires detailed inputs, including chemical kinetics, catalyst properties, exhaust gas characteristics, and composition.

A sensitivity analysis was conducted on the diesel-based SCR model, focusing on parameters such as temperature, ammonia dosing, NO/NOx ratio, and mass flow rate, as shown in Fig.6. The key findings from this analysis are as follows:

- *Temperature:* NO_x conversion efficiency (DeNOx) presents a direct relationship with SCR temperature. It reaches a maximum value within an optimal temperature range and then starts declining at higher temperatures after an optimal point. The modelling results are well aligned with the data available in the literature on the temperature effect.
- *Ammonia Dosing:* An increase in NH_3 dosing also relates with improved NO_x conversion. However, after a certain limit, excessive dosing does not further improve NO_x reduction and may lead to increased ammonia slip.
- *NO/NO_2 Ratio:* An equimolar NO/NO_2 ratio results in higher $DeNO_x$ efficiency at consistent ammonia dosing rates. This effect is more prominent at lower temperatures.

The analysis also highlights the significance of ammonia storage on the catalyst surface. During engine operation, Diesel Exhaust Fluid (DEF) dosing occurs to achieve the desired NO_x conversion. Not all dosed ammonia is immediately utilized; a portion is adsorbed onto catalyst sites, contributing to a reservoir of stored ammonia. This stored ammonia facilitates prompt NO_x reduction in subsequent engine cycles, provided other conditions are optimal.

The initial NO_x conversion rate is influenced by the extent of ammonia coverage on the catalyst, as illustrated in Fig 7. Conversion rates increase with ammonia coverage up to



NH3 Dosing	Temp	Symbol	NH3 Dosing	Temp	Symbol
0.00045	200	━	0.00045	286	┅
0.00034		━	0.00034		┅
0.00025		━	0.00025		┅

Figure 6: NOx conversion for different NO/NOx ratios at different temperatures and dosing rates (Solid lines represent 200°C temperature and dashed lines represent 286°C temperature; different color represents different ammonia dosing)

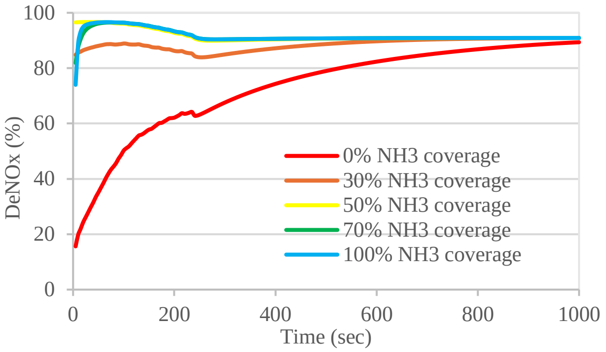


Figure 7: Modelling results of NOx conversion at different coverages for Diesel SCR at 25% engine load

approximately 50%, beyond which the rate may slightly decline. If hydrogen is added to the system, it will also get adsorbed on the catalyst surface inside the SCR thus reducing the NH_3 adsorption and impacting the SCR's performance.

The amount of unburned H_2 emitted from the engine that reaches the SCR is uncertain. In most conditions, much of the H_2 will oxidize in the DOC and DPF, leaving less H_2 for reaction inside the SCR. However, H_2 in the DOC will tend to promote the conversion of NO into NO_2. Higher NO_2/NO ratios (lower NO/NOx in Fig. 6) can help to promote SCR at low temperatures, even if no H_2 is directly reacting in SCR. [7] The behavior of EATS components can be interpreted through the model using experimentally measured data and comparing the results. Modeling and sensitivity analysis, along with experimental data, are important to understand the performance of H_2-DF aftertreatment system.

IV. CONCLUSION

Integrating hydrogen into existing diesel-powered heavy-duty vehicles influences both emission and the performance of exhaust aftertreatment systems (EATS). The presence of H2 impacts the system component temperatures in the EATS. In H_2-DF operation, the DOC shows temperature increase. The EATS takes 5 to 8 minutes to stabilize, with the SCR being the slowest to reach stable conditions. Sensitivity analyses of diesel-based SCR models highlighted the impact of SCR operating temperature, the ratio of NO to total NOx, the amount of ammonia stored on the catalyst, and the quantity of Diesel Exhaust Fluid (DEF) dosed on its performance.

A summary of the key points concluded from this study is as below:

1. Hydrogen addition effectively lowers CO and CO_2 emissions at low load but increases the water content, which may impact the SCR performance.
2. Temperature evaluation shows a higher temperature increase across the DOC for H_2-DF, unlike in diesel operation
3. SCR conversion efficiency is sensitive to the initial conditions (i.e. the urea dosing and the NH_3 stored on the catalyst, as demonstrated by the modelling work) as well as the stabilization time.
4. Under these conditions, tailpipe NOx emissions were low for both diesel and H_2-DF operation despite the low-load.
5. At low load conditions, the stabilization time for the EATS is long: especially for the SCR. While in-service engines will rarely be fully stable, the system must be allowed to stabilize to reliably assess the implications of H_2-DF operation on SCR performance and tailpipe NOx emissions.

These findings emphasize the need to achieve a balance between emission reductions and aftertreatment system performance.

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