Emission Measurement with NOx Sensors in the Presence of HC’s & H_2

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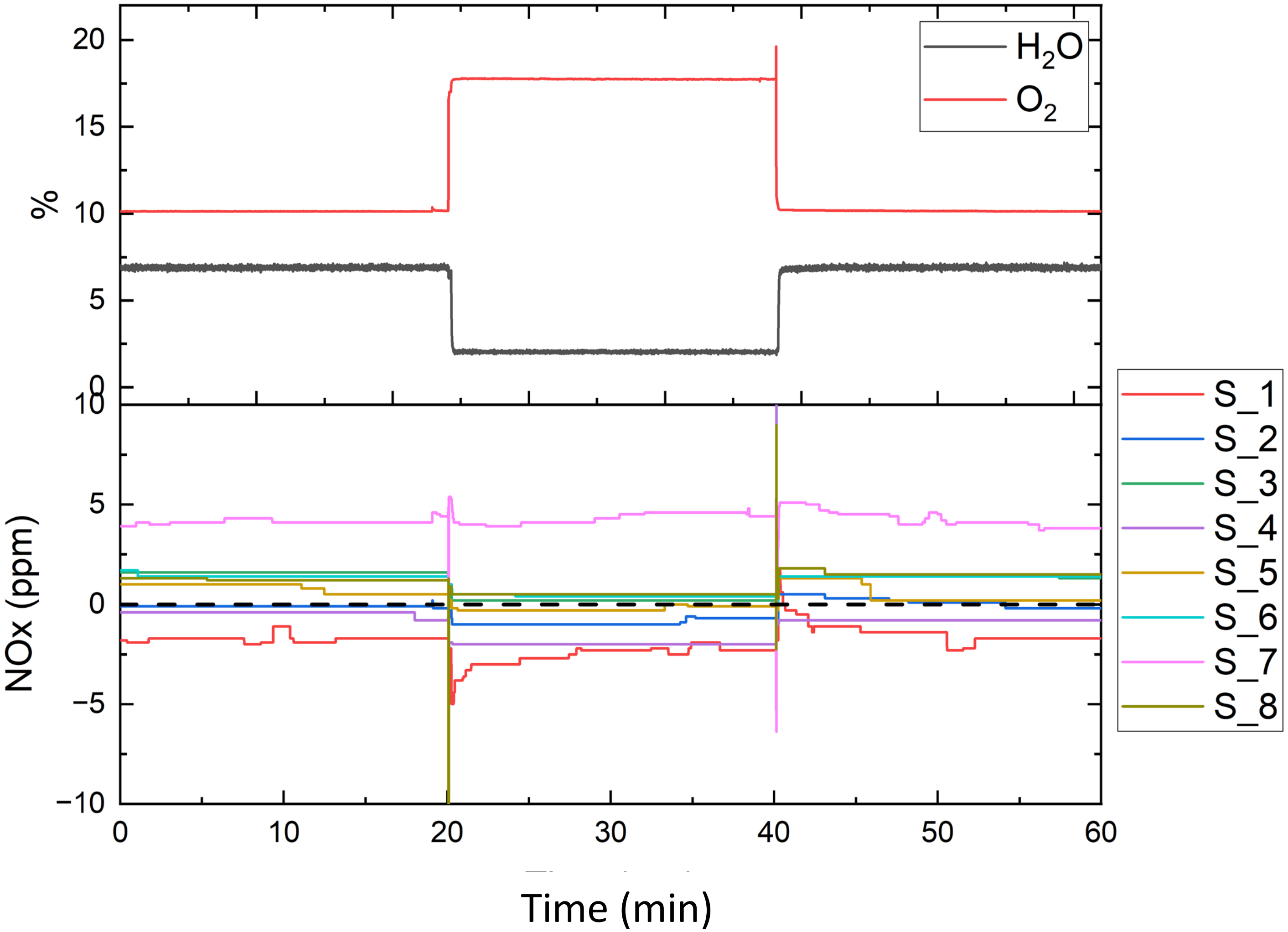
State 1: **7% H_2O, 10% O_2, 6.5% CO_2**

State 2: **2% H_2O, 17.5% O_2, 2% CO_2**

0ppm NOx, fast O_2 Change:

positive drift @state 1

drift lower @ state 2

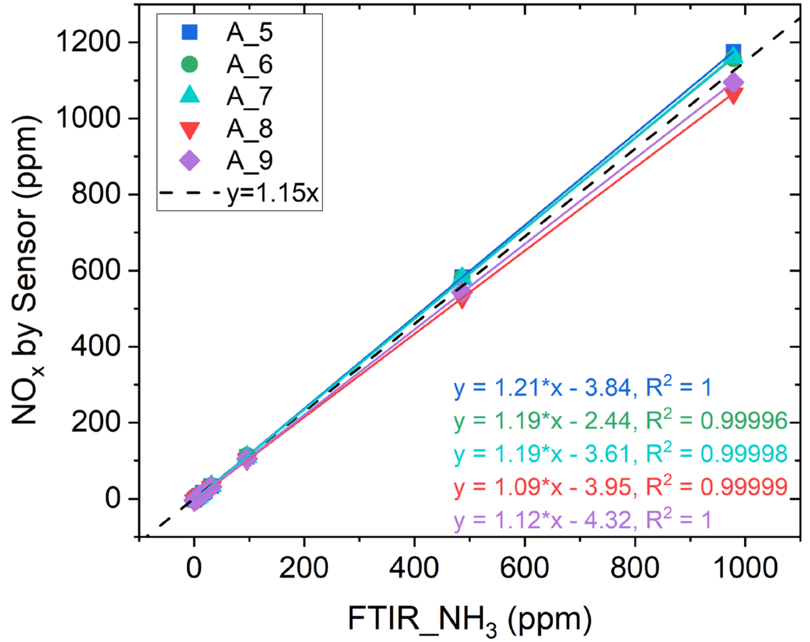


Background

- On-board monitoring relies on the vehicle's sensors to continuously monitor emissions for emissions compliance, system repair, or fleet emissions inventory measurement.
- Understanding the performance of NO_x sensor is crucial for both lean and stoichiometric internal combustion engine (ICE) applications as their sensitivities may vary.
- NO_x sensors measure both O_2 and NO_x while being cross-sensitive to several species on each channel.
- Here we characterize and discuss NO_x sensor cross-sensitivities to various reducing agents in the context of stoichiometric CNG engines and H_2-ICE applications.

Potential NO_x/NH_3 Emission Deconvolution Method for Stoichiometric Applications

- NO_x sensors have a well known cross-sensitivity on their NO_x channel to NH_3 (see right).
- For stoichiometric-ICE applications both NO_x (lean) and NH_3 (rich) may be present.
- The proposed method relies on the NO_x sensor's O_2 channel to arbitrate between when the NO_x channel is responding to NO_x (lean) vs NH_3 (rich).



Outstanding Questions:

1. What species/factors impact the sensor's O_2 readings and may negatively impact the sensor's ability to arbitrate between rich and lean vehicle operation?
2. Is the sensor's NH_3 cross-sensitivity consistent across both rich and lean operation?
3. What are the implications of the sensor's H_2 sensitivity for lean burn H2-ICE applications?
4. Are there any situations on stoichiometric systems, healthy or failed, in which you will have the simultaneous presence of NO_x and NH_3 or NO_x when it is rich and NH_3 when it is lean?
5. Are OEM and aftermarket NO_x sensors capable?

Methods: Sensor Exerciser and Test Instrument (SETI)

Primary sensor characterization test bench:

- Temperature Range: 20-550 ^oC.
- Isobaric flow sweep capability (<40 psi).
- Flow Range: 20 – 250 SLPM.
- ≈0.2 sec response time measurements.
- Independently controlled H_2, CH_4, C_3H_8, CO, CO_2, N_2, O_2, H_2O, NO, NO_2, & NH_3 concentrations.

Features

FTIR

O_2 Analyzer

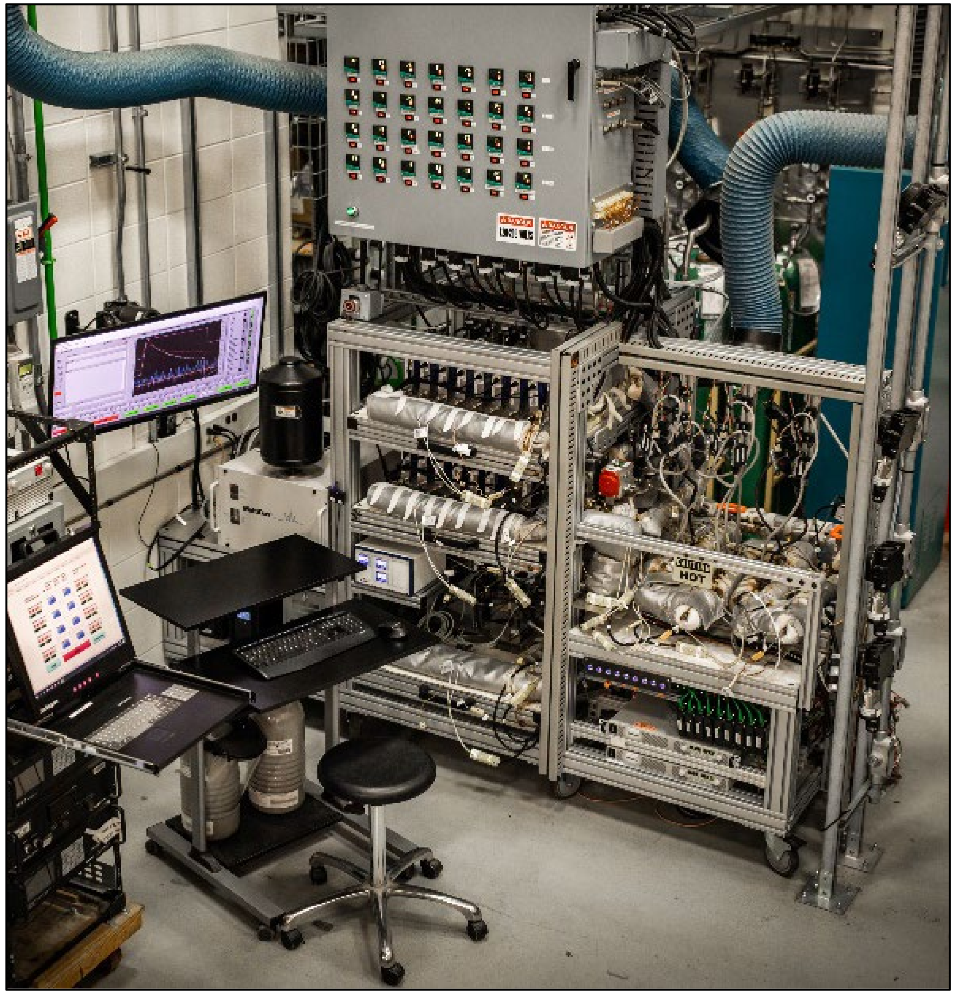
NDUV (NOx)

Thermal MFCs

Coriolis MFCs

Humidity Sensors

Pressure Sensors



Here we tested with two HC mixtures:

- Mix1: 1% CO, 3000 ppm H_2, 3000 ppm CH_4, 0 ppm NO, at 150 °C.
- Mix2: 0% CO, 0 ppm H_2, 2200 ppm CH_4, 0 ppm NO, at 350 °C.

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Concept Introduction: “Net O_2”

- Net O_2 is the O_2 concentration less the concentration of reducing agents as considered based on the amount of O_2 needed to fully oxidize said reducing agents.
- OBD-style NO_x and O_2 sensors are designed/expected to measure “Net O_2” and not O_2 concentration.
- When “Net O_2” = 0% we consider this to be the definition of the λ=1, stoichiometric condition. All “rich” conditions are defined by Net O_2 concentrations less than zero whereas “lean” conditions correspond to positive Net O_2 concentrations.
- Example Calculation:
    - O_2 concentration = 10% as measured by a reference analyzer (e.g. paramagnetic)
    - CH_4 concentration = 2% as measured by a reference analyzer (e.g. FTIR)
    - H_2 concentration = 1% as measured by a reference analyzer (e.g. mass flow meters)

$$\mathrm{CH_4} + 2 \cdot \mathrm{O_2} \rightarrow \mathrm{CO_2} + 2 \cdot \mathrm{H_2O} \qquad (1)$$

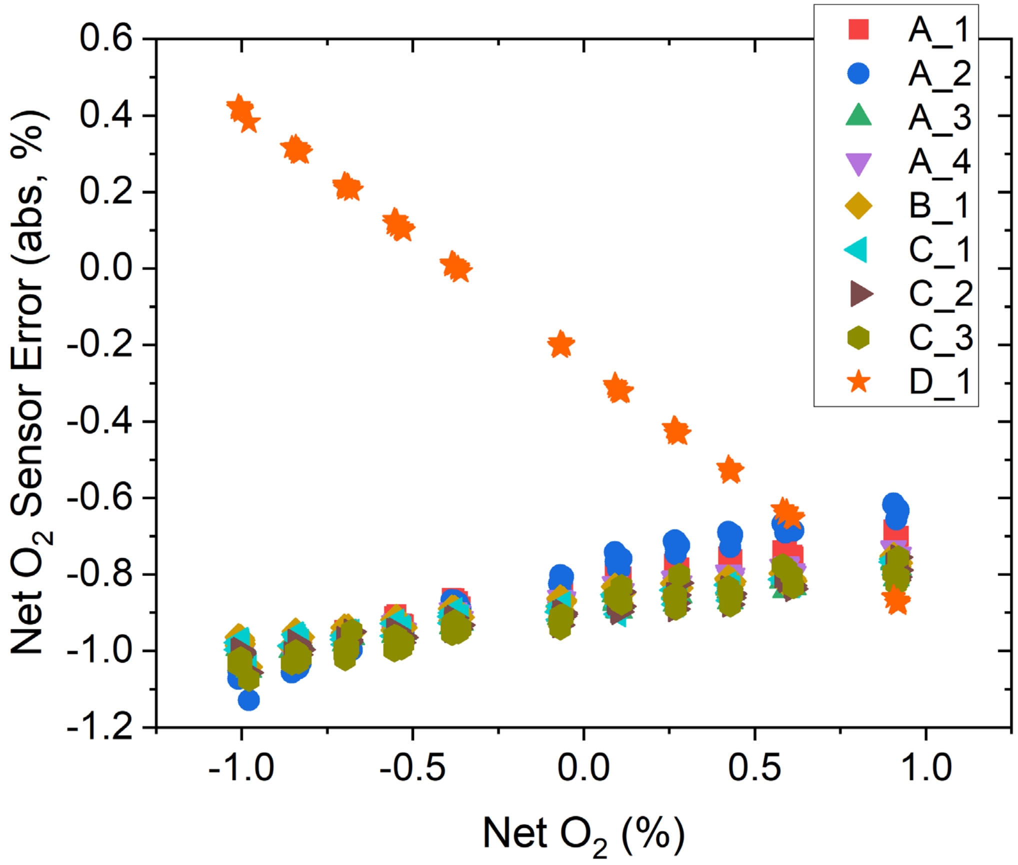
$$\mathrm{H_2} + \frac{1}{2} \cdot \mathrm{O_2} \rightarrow \mathrm{H_2O} \qquad (2)$$

    - Net O_2 = 10% - 4% (CH_4) – 0.5% (H_2) = 5.5%

O_2 Channel Accuracy with NH_3 vs. λ (HC Mix 1)

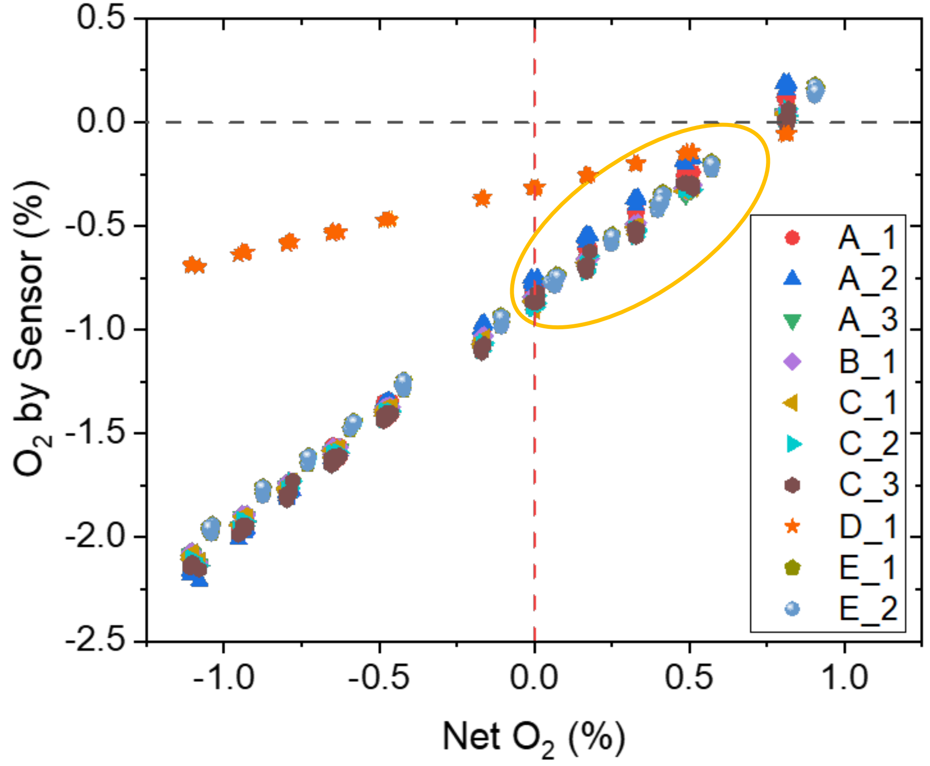
Test condition:

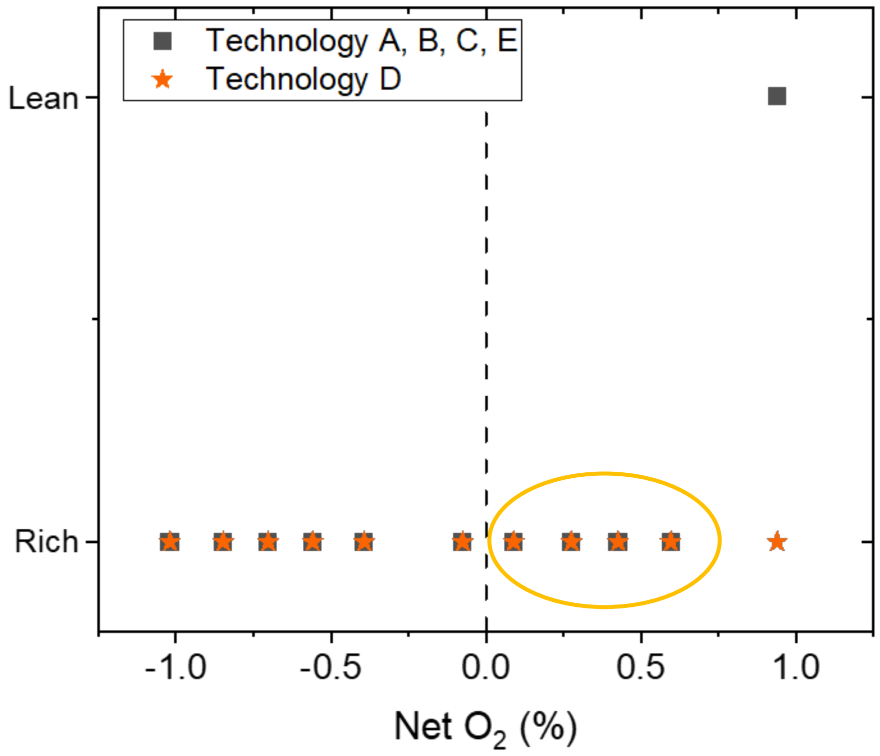
- 1% CO, 3000ppm H_2, 3000ppm CH_4, 0ppm NO
- 150^{o}C
- NH_3: 256, 128, 64, 32, 16, 8, 0ppm (multiple points for each sensor at each O_2 concentration)



- Sensor technologies A, B, C are showing a weak positive dependence as O_2 increases and an overall negative bias.
- Sensor technology D is showing a negative dependence as O_2 increases.

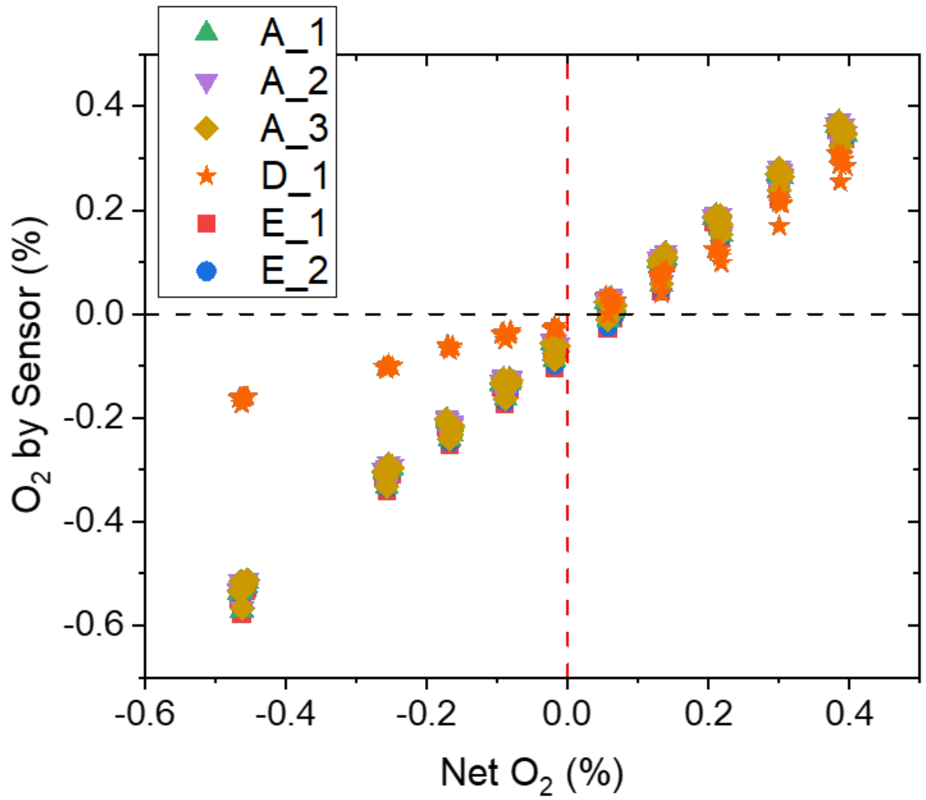
O_2 Arbitration – Lean vs Rich with HC Mix 1?

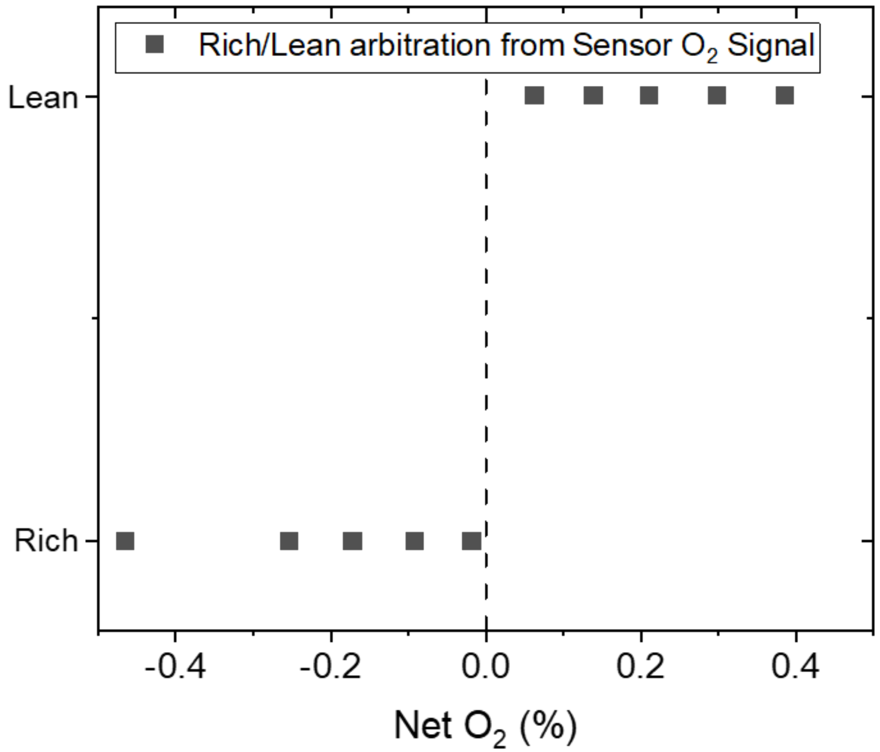




- 1% CO, 3000 ppm H_2, 3000 ppm CH_4, 0 ppm NO, at 150 °C.
- The NO_x sensors are under-reporting the O_2 level and read rich when it's lean.

O_2 Arbitration – Lean vs Rich with HC *Mix 2*?



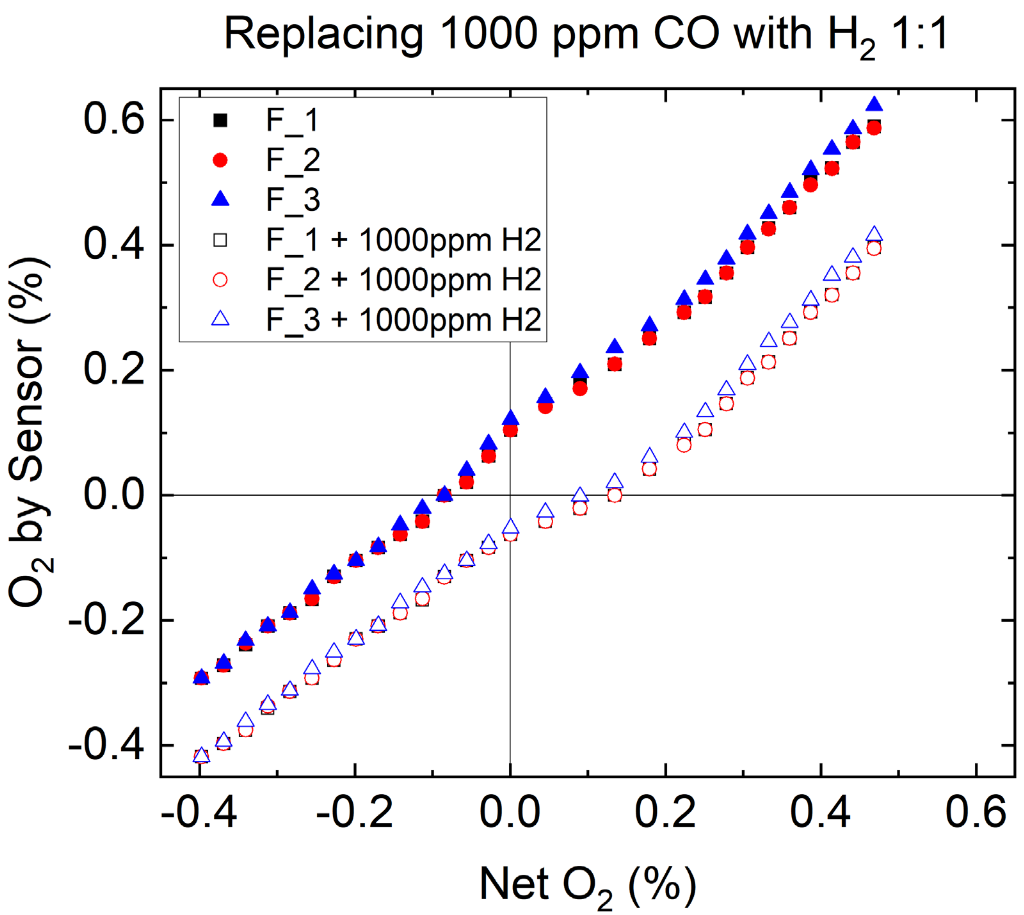


- 0% CO, 0 ppm H_2, 2200 ppm CH_4, 0 ppm NO, at 350 °C.
- NH_3: 256, 128, 64, 32, 16, 8, 0ppm.
- The NO_x sensors are *slightly* under-reporting the O_2 level and could distinguish rich vs lean.

Sensor Supplier Observations:

HC Mixtures of Propane, CO, and H_2

- Schaeffler tested with fixed concentrations of C_3H_6 and variable amounts of O_2, CO, & H_2.
- Two tests were done with one test exposing the sensors to 1000 ppm more H_2 at each point which was offset by a 1000 ppm decrease in CO (unchanged λ).
- Sensors exposed to higher H_2 concentration were biased lowe by the exposure.
- Presence of the heavy molecule C_3H_6 might be the cause of th observed lean bias under some conditions.



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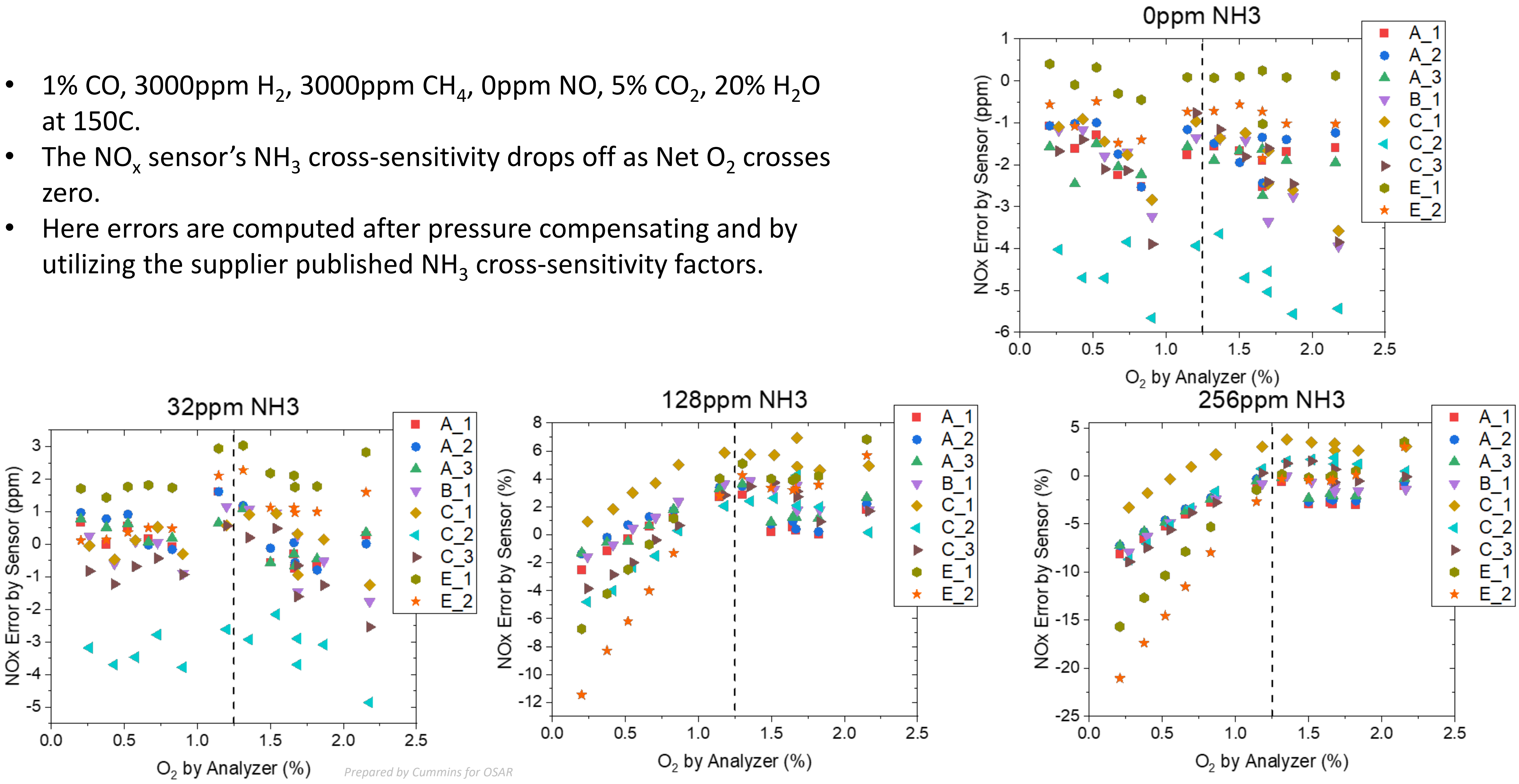
Data provided courtesy D. Wieland, Schaeffler Automotive Group

NO_x Channel NH_3 Sensitivity Variability vs O_2

- 1% CO, 3000ppm H_2, 3000ppm CH_4, 0ppm NO, 5% CO_2, 20% H_2O at 150C.
- The NO_x sensor's NH_3 cross-sensitivity drops off as Net O_2 crosses zero.
- Here errors are computed after pressure compensating and by utilizing the supplier published NH_3 cross-sensitivity factors.



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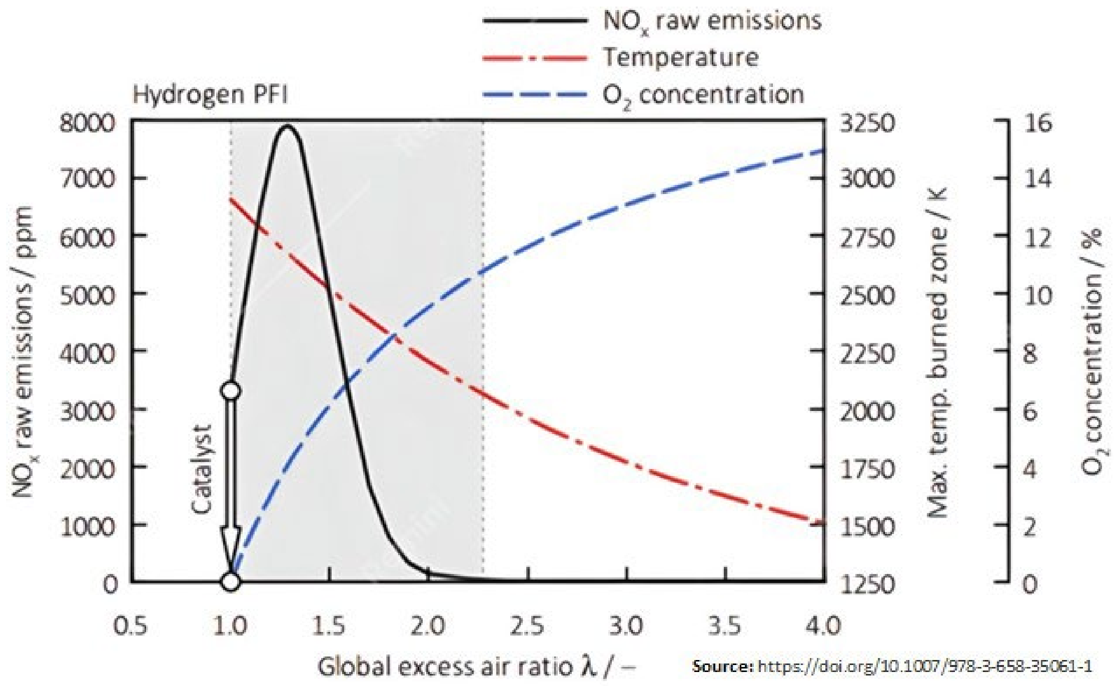
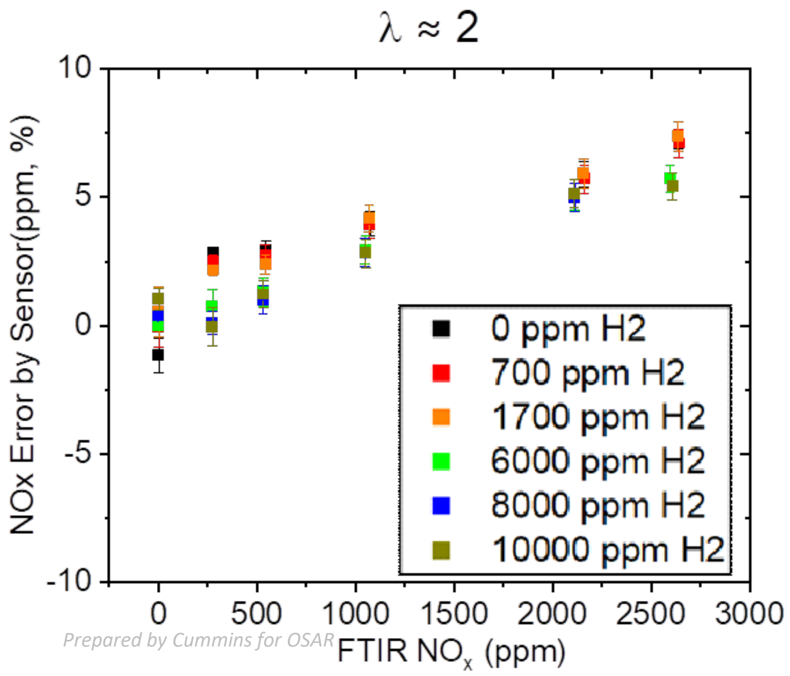
Applicability for H_2-ICE

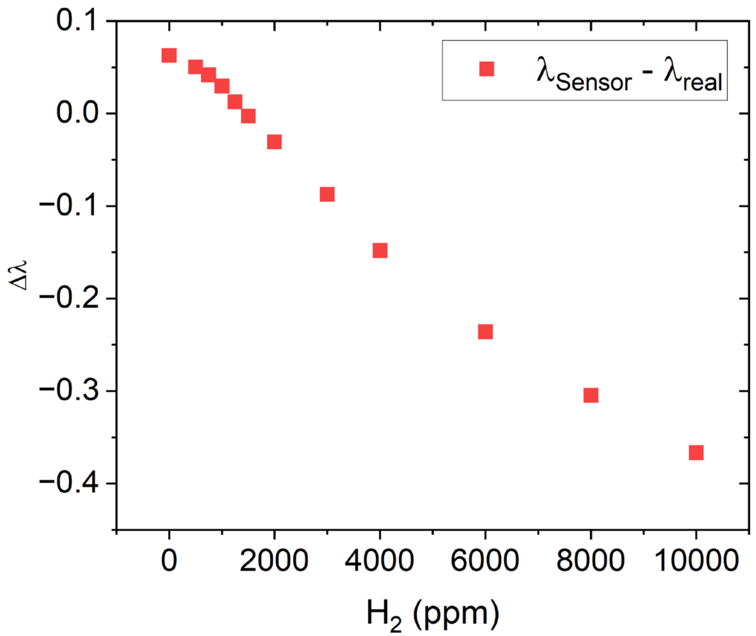
- The measured H_2 sensitivity on the O_2 channel is ~4x the sensitivity needed for the sensor to serve as a consistent indicator of λ (i.e. ~2 vs ½).

$$\mathrm{H_2} + \frac{1}{2} \cdot \mathrm{O_2} \rightarrow \mathrm{H_2O}$$

- The NO_x channel is largely insensitive to H_2.







Conclusions & Next Steps:

Conclusions:

- We found that the sensor's O_2 readings are particularly impacted by H_2 which induces a rich bias under both truly rich and truly lean conditions alike.
- If H_2 were to exist under lean conditions, it could lead to a sensor's broadcast NOx values to be erroneously associated with NH_3 emissions.
- Both positive and negative biases of the sensor's O_2 channel are possible with highly diffusive reducing agents biasing the net O_2 reading low and slower molecules potentially imposing a high bias.
- NH_3 sensitivity remains *relatively* consistent around λ=1 especially at lower NH_3 levels.
- The method considered for NO_x monitoring on stoichiometric applications may have issues under some conditions while working fine under others.

Potential Next Steps:

1. Get a better understanding of the real-world H_2 + HC + CO concentrations at the tailpipe for both healthy and degraded systems.
2. Consider a combined NO_x+NH_3 threshold based approach.
3. Characterize alternatives technologies:
    - Aftermarket NOx sensors
    - Traditional wideband and narrowband O_2 sensors
    - H_2 sensing technologies for compensation

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Q+A