Laboratory Investigation of Exhaust NO_X/NH_3 Sensors for Onboard Emissions Monitoring

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Acknowledgements

- This phase of the work was funded by the Truck & Engine Manufacturers Association (EMA).
  - The system data acquisition and sensors were later used on sensor work on SwRI ECTO-LAB, funded by EPA, and not covered in this presentation
  - The same system will be used on SwRI ultra low NO_X engine platform with portions funded by EPA and EMA
- The sensor manufacturers Bosch, Denso, Delphi and Continental contributed in-kind sensors and technical support

Objectives

- The objectives of this work are to:
  - Develop and apply a CFR Part 1065 bench-test procedure to investigate NO_X/NH_3 sensors like that used for laboratory or field instruments for:
    - Accuracy, Repeatability, Noise, Linearity and Response Time
  - Verify the performance of sensors at various NO_X/NH_3 levels ranging from 0 to 1500 ppm
  - Make the data acquisition system and data logging adaptable to various applications beyond bench-testing to include sensor work on SwRI ECTO-LAB and engine work

Note that currently there is no bench-testing procedure per CFR for sensors like laboratory instruments and field instruments. This is done only as a reference.

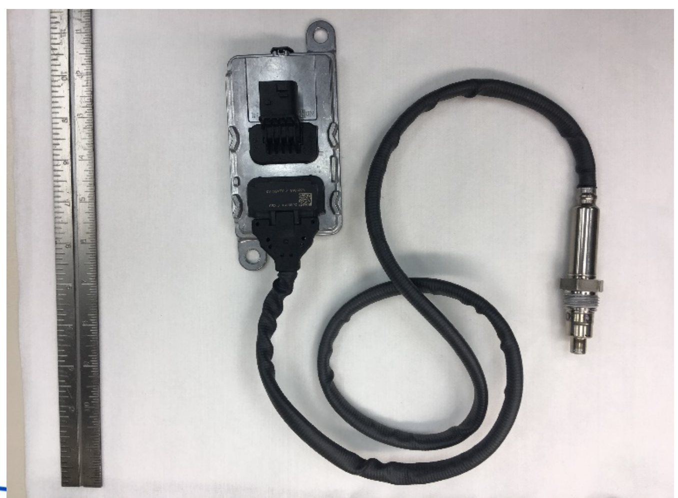
Test Sensors Received By SwRI

https://www.swri.org/swri-automotive-webinar-obd

Denso NOx sensor

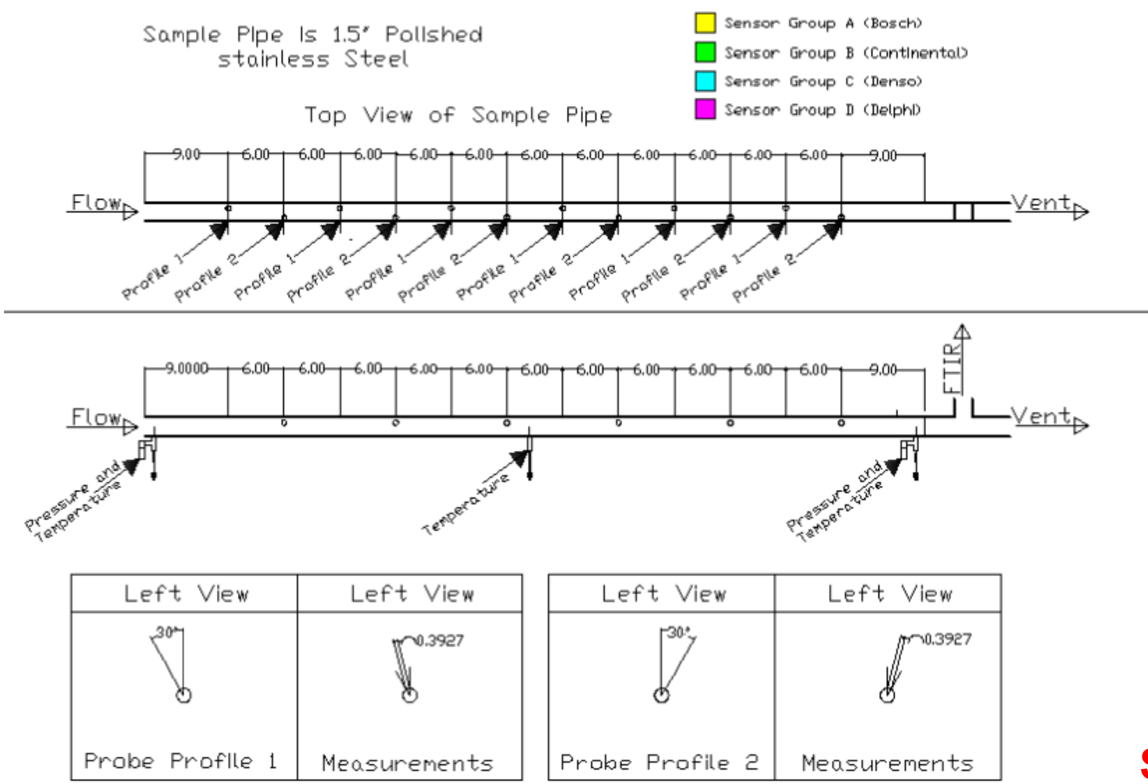
Bosch NOx sensor

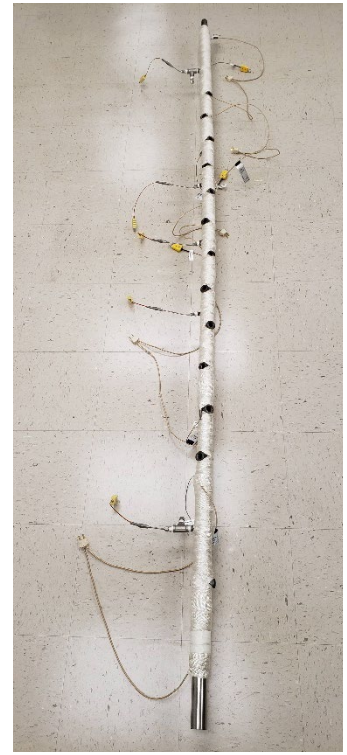
Continental NOx sensor



Delphi NH_3 sensor

Test Sample Pipe





Sample pipe with heat wrap and insulation

- Highly polished stainless-steel pipe
- Heated to 191˚C with verified temperature distribution

Experimental Schematic/Target Matrix

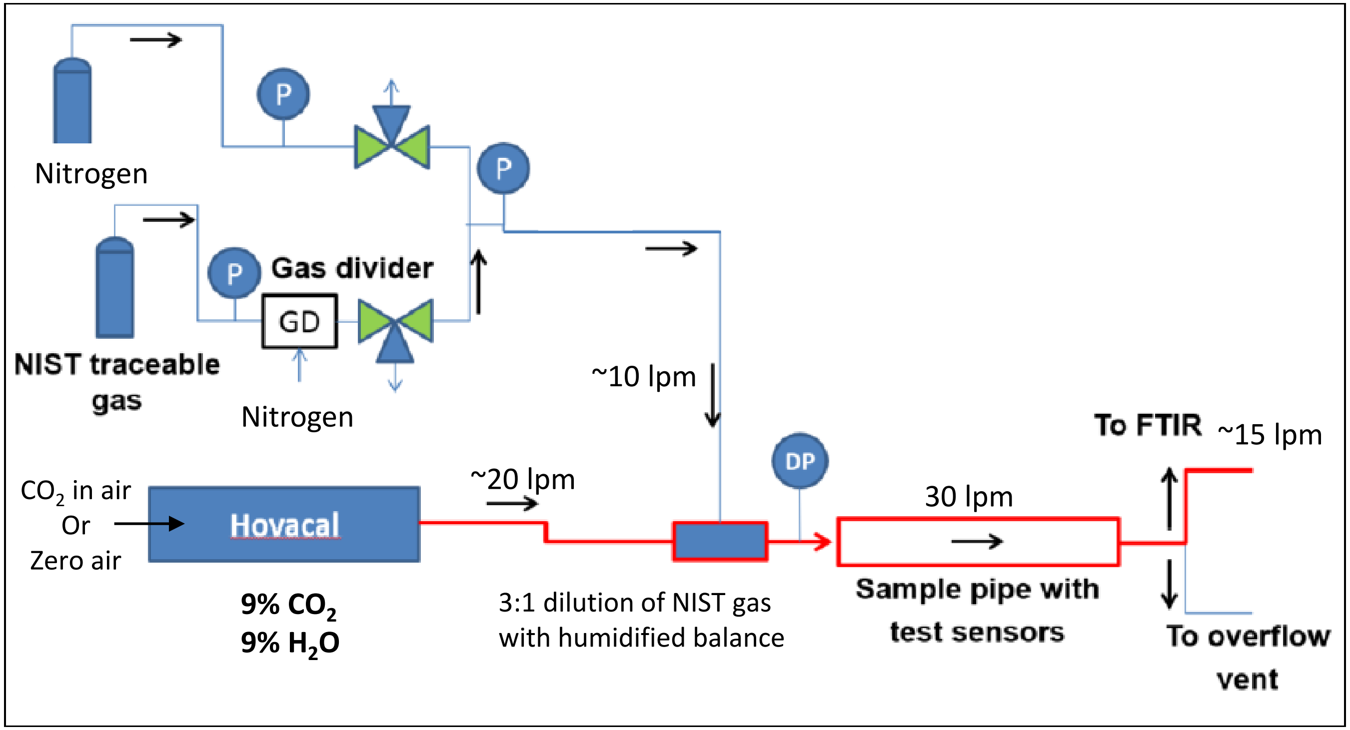
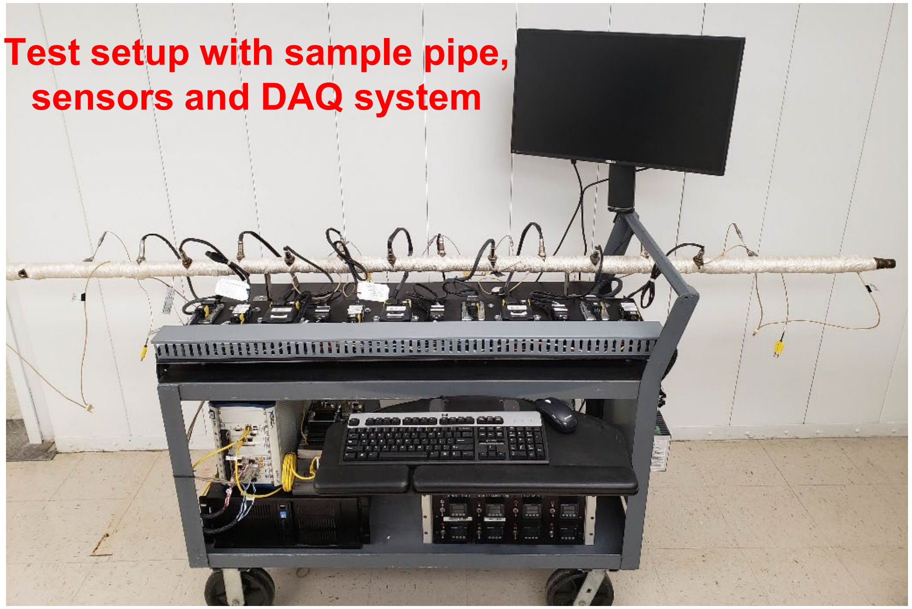


FIGURE 1. SCHEMATIC OF TEST SETUP FOR CALIBRATING SENSORS

TABLE 1. CALIBRATION RANGE FOR EACH GAS

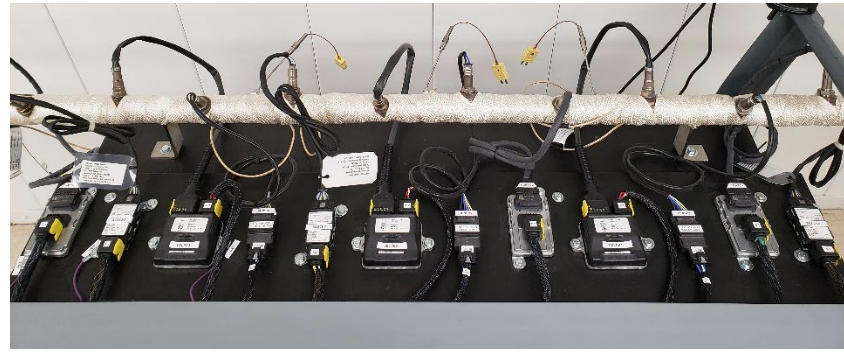
Gases	Calibration range	Span bottle 1	Span bottle 2	Span bottle 3
NO	0 to 1500 ppm	75 ppm to 1500 ppm	5 ppm to 100 ppm	0.5-10 ppm
NO_2	0 to 1500 ppm	75 ppm to 1500 ppm	5 ppm to 100 ppm	0.5-10 ppm
NH_3	0 to 1500 ppm	75 ppm to 1500 ppm	5 ppm to 100 ppm	0.5-10 ppm

Experimental Setup – Sensors, Pipe and DAQ

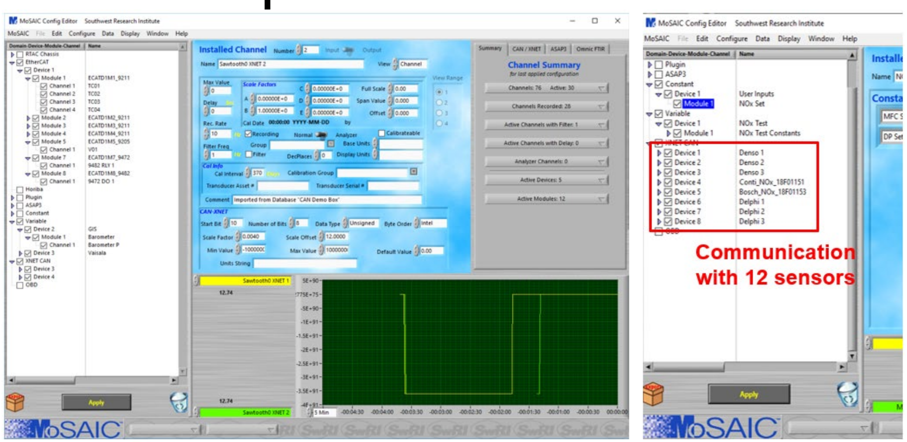


Test setup with sample pipe, sensors and DAQ system

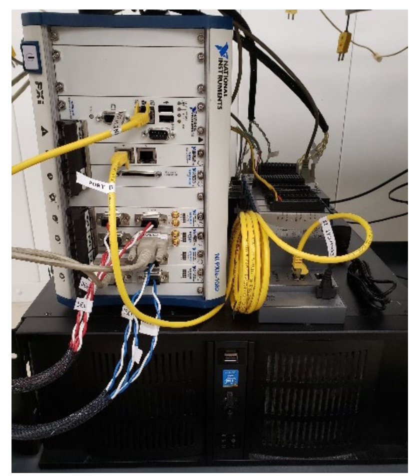
Sensor setup



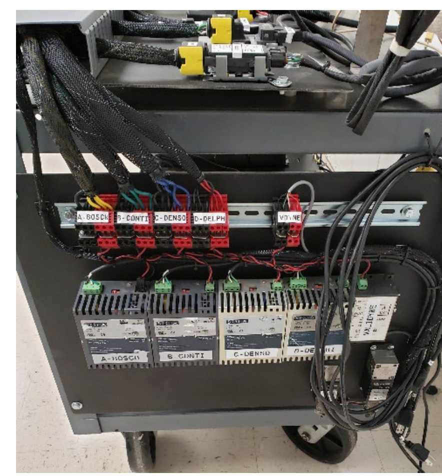
- Data Acquistion



DAQ setup



Power supply setup



Accuracy, repeatability and noise verification– CFR 1065.305

1. Supply a reference concentration y_{ref} from NIST bottle and allow time for signal stabilization
   - Record data for 30 seconds. Calculate $\overline{y_i}$ and σ_i
   - Calculate error $\varepsilon_i = \overline{y_I} - y_{ref}$
2. Repeat 10 times $(\overline{y_1}, \overline{y_2}, \overline{y_i}, \ldots\overline{y_{10}}), (\sigma_1, \sigma_2, \sigma_i, \ldots\sigma_{10}), (\varepsilon_1, \varepsilon_2, \varepsilon_i, \ldots\varepsilon_{10})$

- **Accuracy**
  - *Absolute*$|(y_{ref}$ (or $\overline{y_{ref}}$) - mean of the ten $\overline{y_i}$, (or $\overline{y}$)$|$
- **Repeatability**
  - Two times stdev of the ten errors
  - Repeatability = $2 \cdot \sigma_{\varepsilon}$
- **Noise**
  - Two times RMS of the ten stdevs
  - Noise = $2 \cdot rms_{\sigma}$

Linearity Verification – CFR 1065.307

Use the ten $\bar{y}_i$, and reference values, y_{refi} to develop linear regression

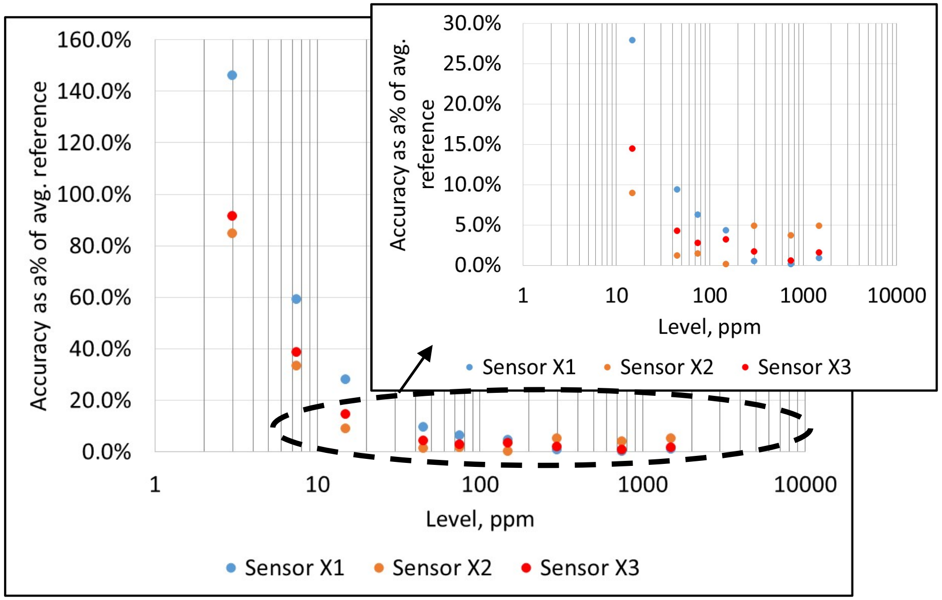
– Slope (a_{1y}), Intercept (a_{0y}), SEE and r^2

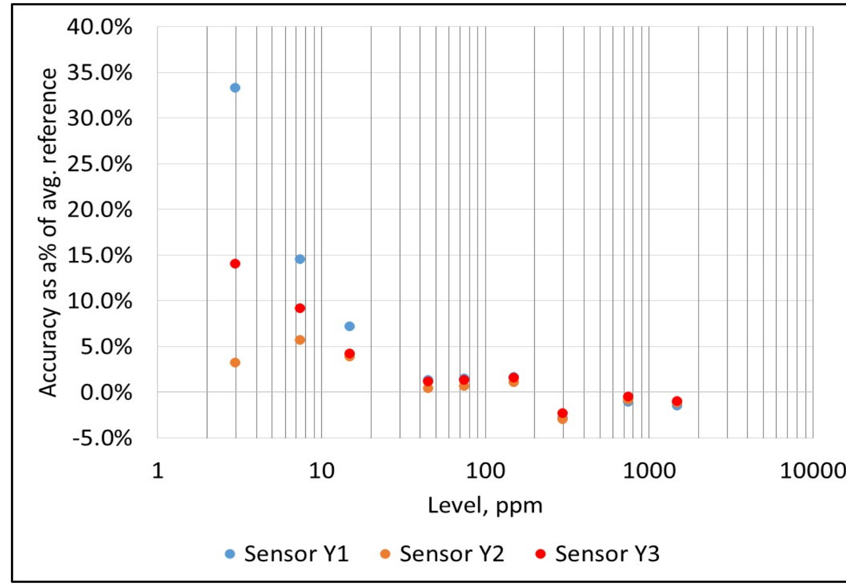
Measurement system	Quantity	Linearity criteria			
		$\lvert x_{min}(a_1-1) + a_0 \rvert$	a_1	SEE	r^2
Gas analyzers for laboratory testing	x	$\leq 0.5\% \cdot x_{max}$	0.99-1.01	$\leq 1\% \cdot x_{max}$	≥ 0.998
Gas analyzers for field testing	x	$\leq 1\% \cdot x_{max}$	0.99-1.01	$\leq 1\% \cdot x_{max}$	≥ 0.998

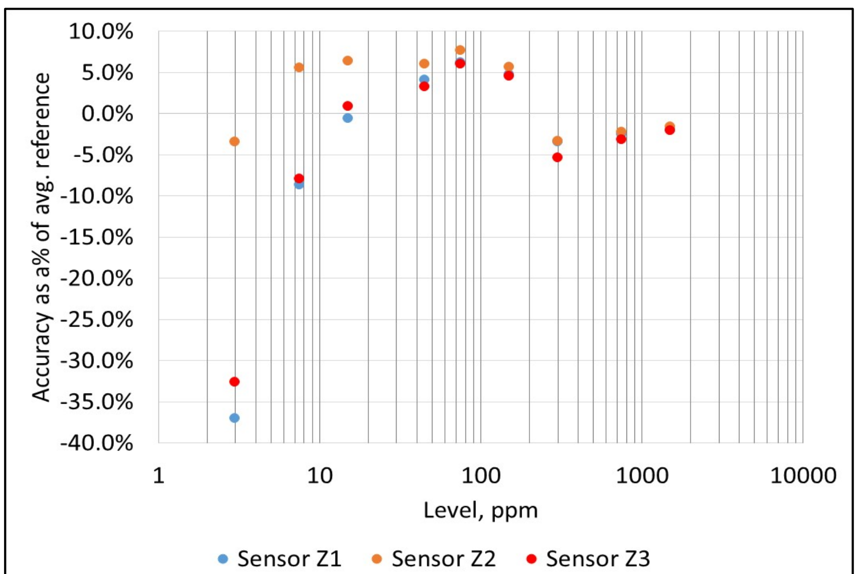
Response time – CFR 1065.308

Calculate the mean rise time, $t_{10\text{-}90}$, and mean fall time, $t_{90\text{-}10}$

NO Gas Results – Relative Accuracy of Sensors

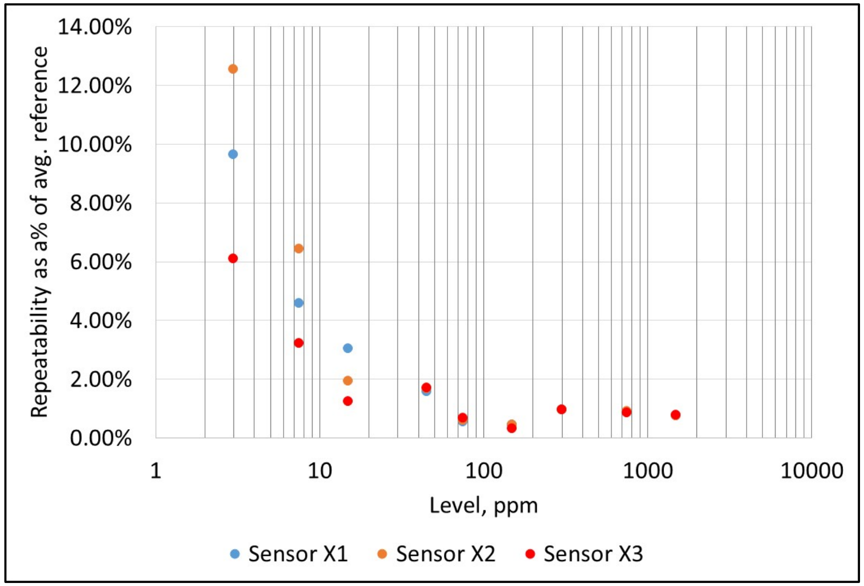


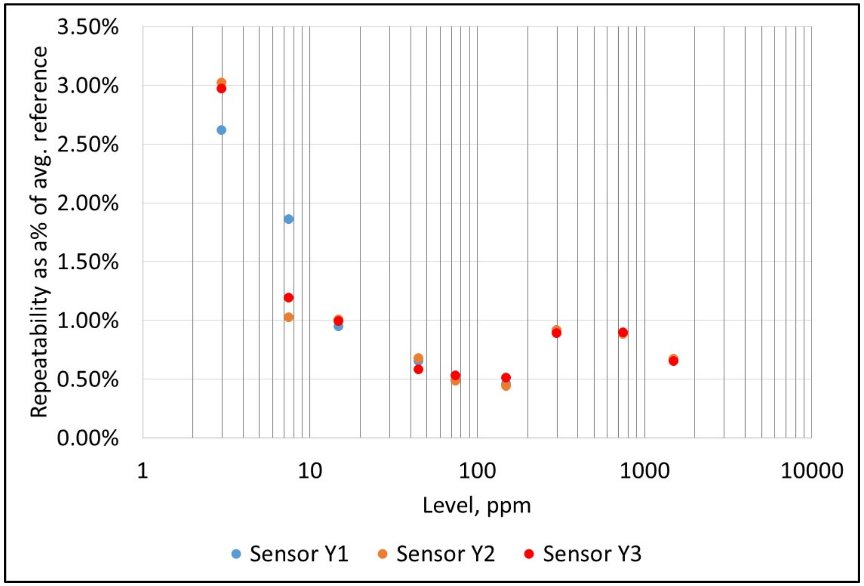


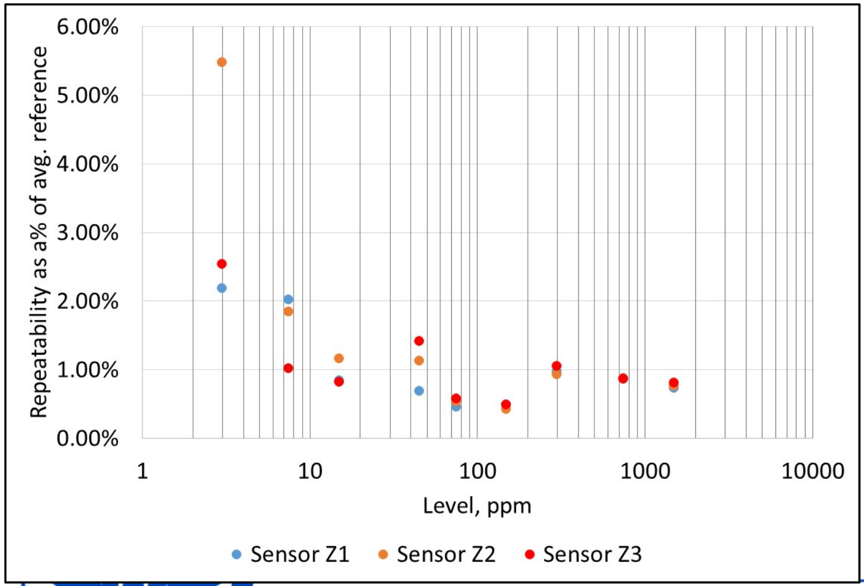


- For each manufacturer, all three test sensors performed similarly
- Relative accuracy decreases with decrease in conc. at levels < 10 ppm
- Accuracy improves at higher levels
  - <~5% or less

NO Gas Results – Relative Repeatability of Sensors

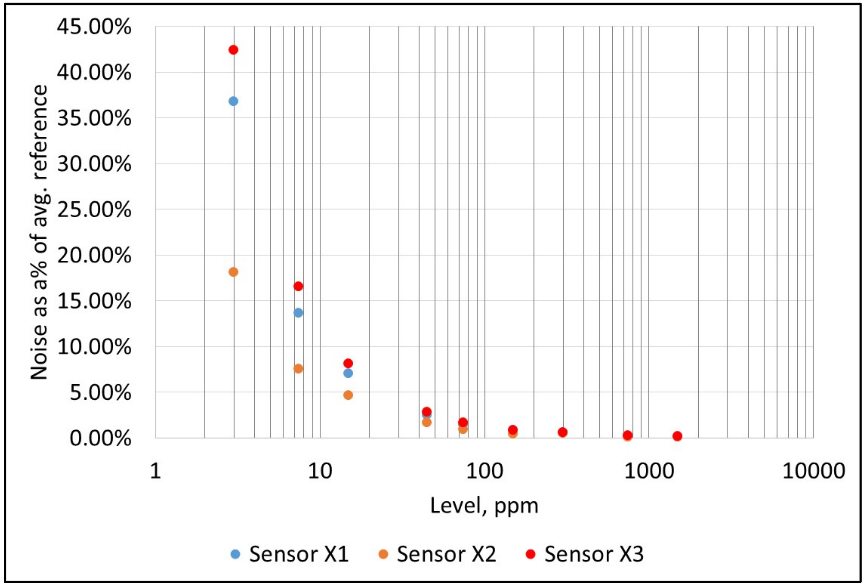


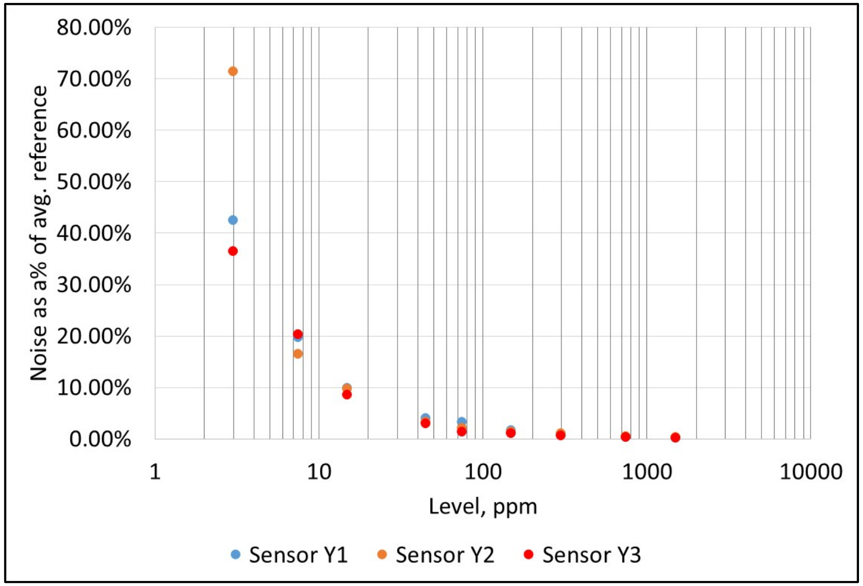


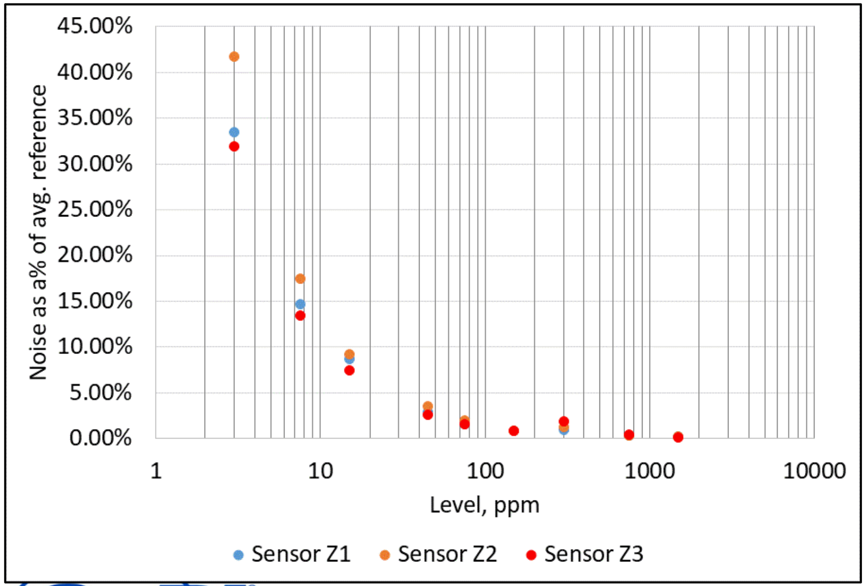


- For each manufacturer, all three test sensors performed similarly
- Repeatability of sensors was 1% to 2% for all sensors at levels > 10 ppm
  - 1% to 12% < 10 ppm

NO Gas Results – Relative Noise of Sensors

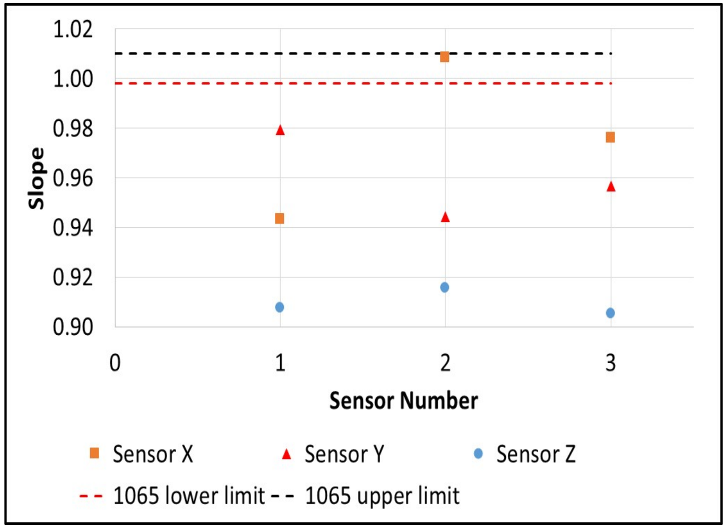


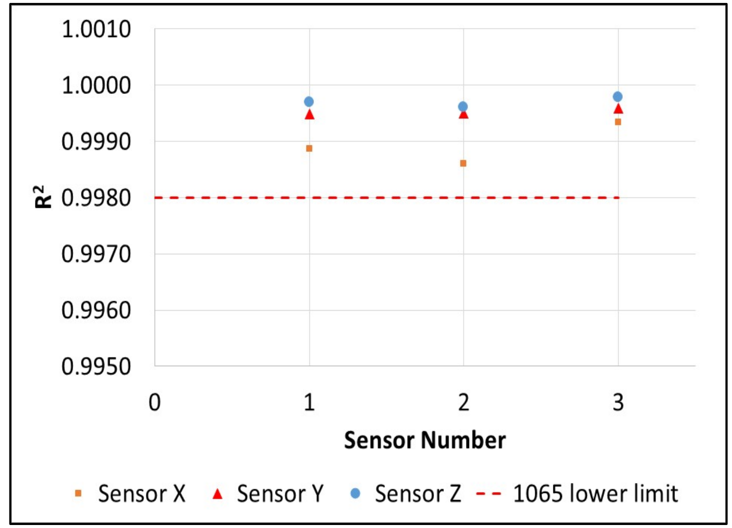


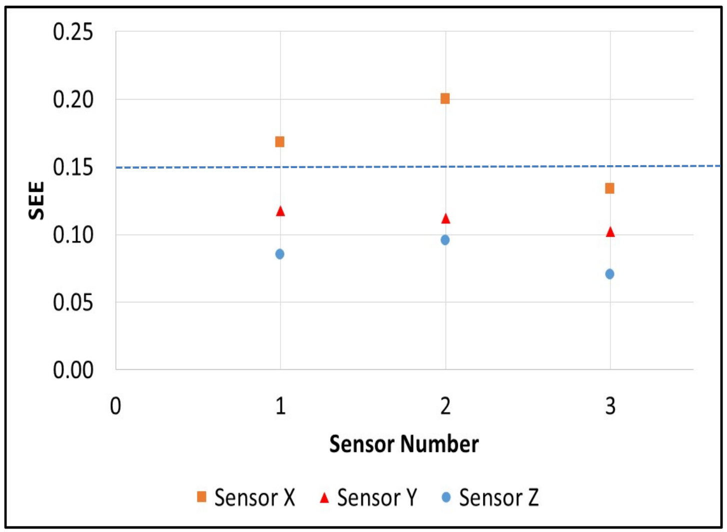


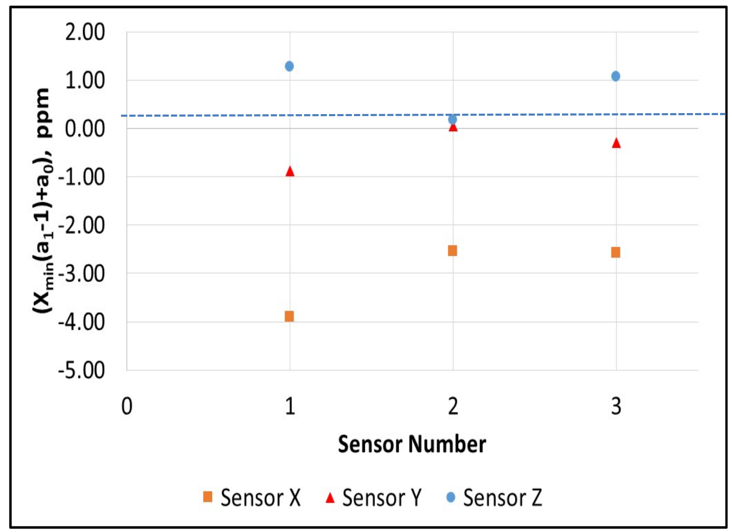
- For each manufacturer, all three test sensors performed similarly
- Noise is about 2% to 3% at levels > 10 ppm
  - Sensors became noisy below 10 ppm, reach 40% to 70% at 3 ppm

NO Gas Linearity (0 to 15 ppm)



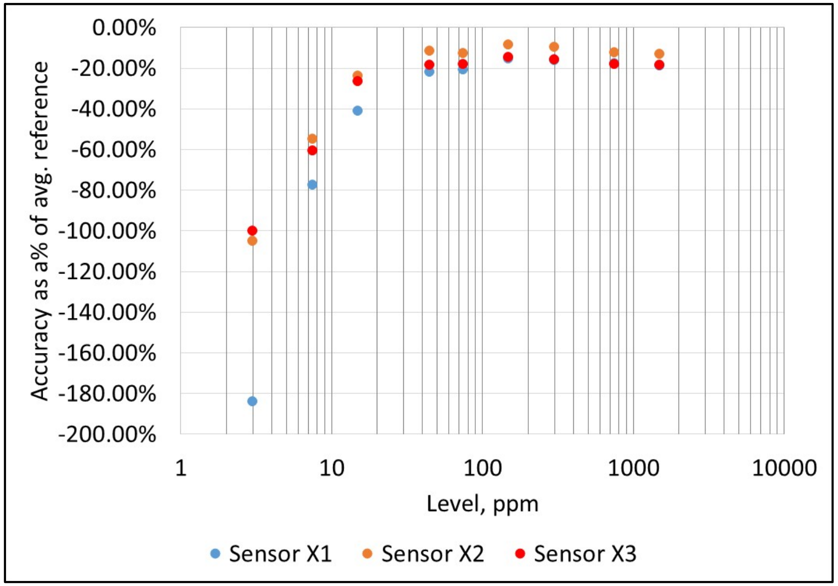


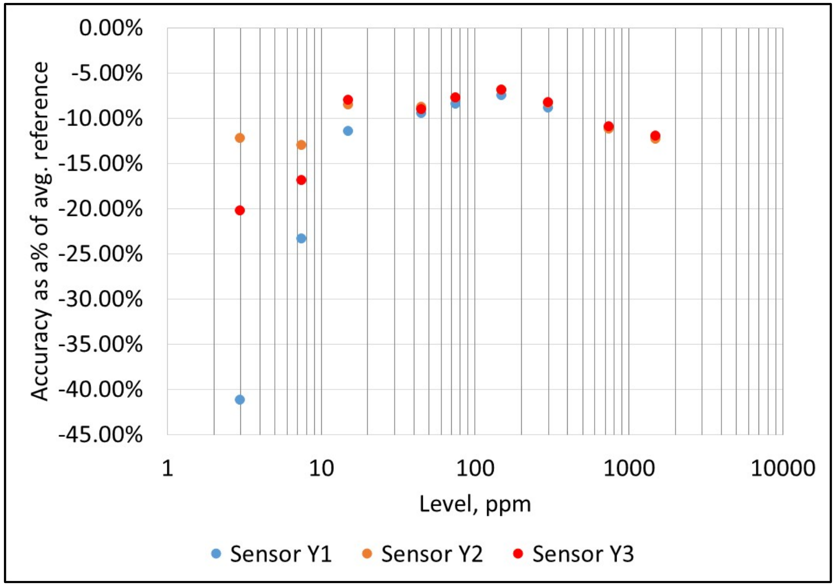


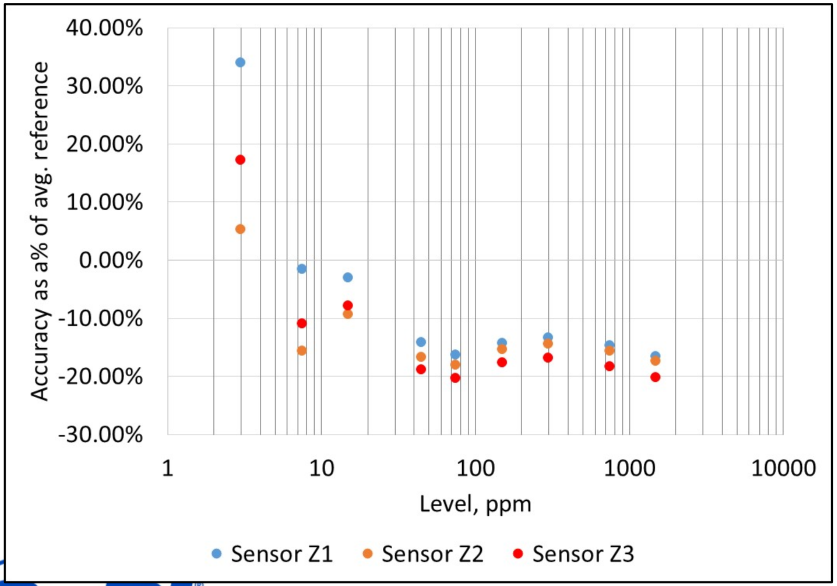


- Sensors passed on R^2, and SEE and failed on slope and Intercept
- Results were similar for higher ranges especially for R2 and Slope

NO_2 Gas Results – Relative Accuracy of Sensors

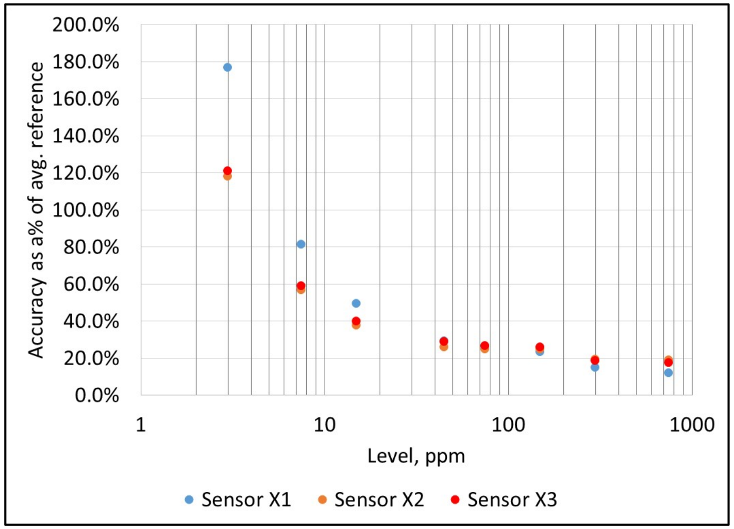


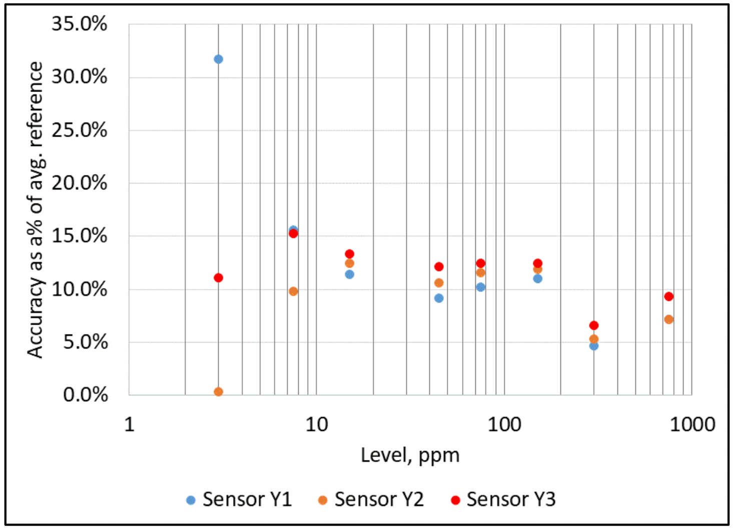


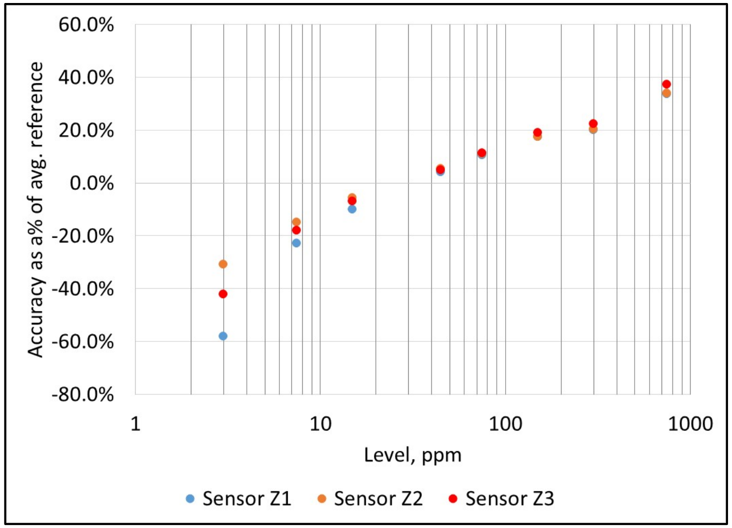


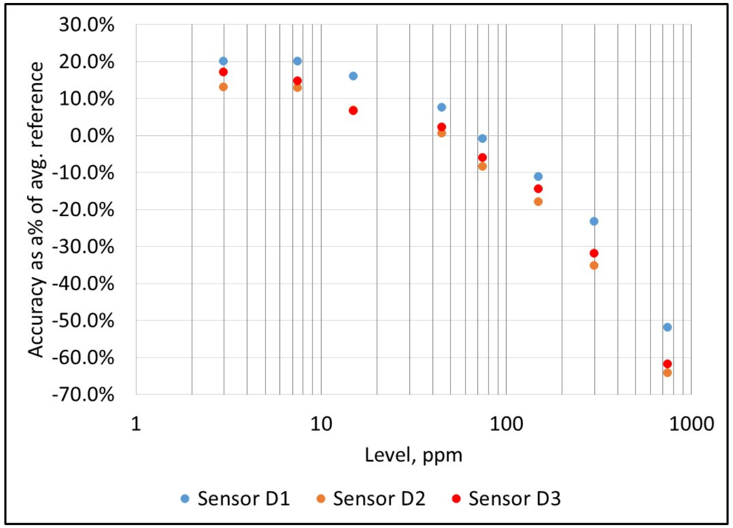
- For each manufacturer, all three test sensors performed similarly
- Sensor generally underestimated NO_2 emissions
- Relative accuracy decreases with decrease in conc. at levels < 10 ppm, but increased for one sensor

NH_3 Gas Results – Relative Accuracy of Sensors



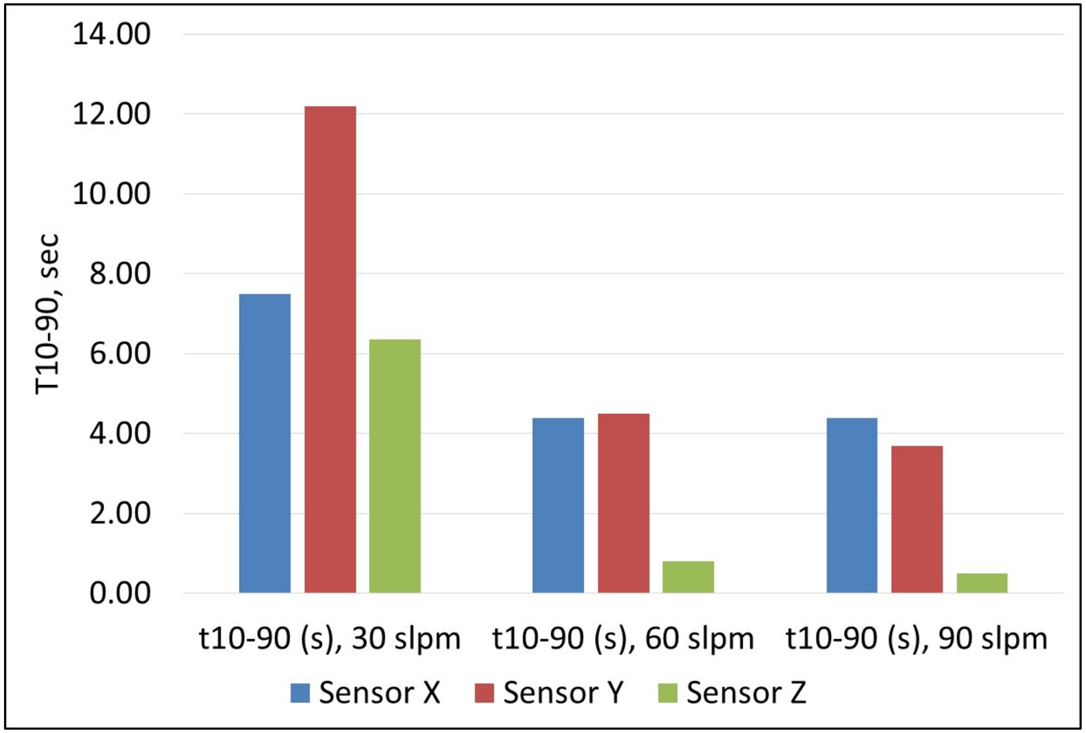






- For each manufacturer, all three sensors performed similarly
- All sensors are sensitive to NH_3

Sensor Response Time – Function of flowrate



- Quick experiment conducted to demonstrate the effect of flowrate on response time
  - Sensor response time decreases with increase in flowrate through the sample pipe

Summary

- Measuring below 5 ppm is challenging to get accurate results to within less than 35%, even under ideal steady-state condition. *This level is approaching the levels to be encountered in 2027 CARB low NOx compliant engines.*
    - More R&D is needed with a focus on the area of sub 10-20 ppm
- Sensors exhibited good repeatability on the order of 5% at 3 ppm, and better repeatability at higher concentration
- Sensors exhibited a noise level on the order of 35% at 3 ppm, and less noise at higher concentration
- Differences were observed in sensor response to NO & NO_2. Sensors' response underestimates NO_2 as the concentration of NO_2 increase
- NH_3 is a major interference to NOx sensors. The NOx sensors responded to ammonia as good as the ammonia sensor. Such interference must be minimized or eliminated

Final Thoughts

- While this work was useful in highlighting some important information about NO_X/NH3 sensor performance, it was limited as it did not address the impact of additional steady-state and transient variables typically encountered in engine exhaust such as:
  - Flow rate, temperature, O_2, H_2O and other variables and their rate of change, especially under transient operation
- The impact of these variables were addressed in a subsequent study at SwRI using ECTO-LAB, followed by current activities being setup on a low NO_X engine
- More work is needed to advance the state of NO_X sensors to yield accurate and repeatable results at tailpipe low-NO_X emission levels