Literature Review Update: PM_{10}, CO, NO_2 and SO_2

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Background

- In 2017 literature review to support the 2018 workshop and performance targets development.
- 2019 update covers the incremental gap
- Focused on information and data from low-cost air sensors used in **outdoor**, **non-regulatory** applications of carbon monoxide (CO), nitrogen dioxide (NO_2), coarse particulate matter (PM_{10}), and sulfur dioxide (SO_2).
- After removing resources pertaining to sensor research and development, EPA assessed a total of 332 resources for applicability and utility.

Background

- EPA grouped the identified resources into one or more of the following categories for further analysis:
  - Performance Assessments, Evaluations, or Specifications.
  - Testing Methodologies and Protocols.
  - Initial and On-Going Calibration.
  - Best Practices Related to Selecting, Deploying, Maintaining, and Assessing Sensors.

Sensor Performance

- For the Sensor Performance category, EPA identified resources related to quantitatively characterizing the measurement performance of air sensors, including field and laboratory evaluations conducted:
  - Solely to assess sensor performance.
  - As part of broader deployment effort or to develop equations for adjusting or correcting sensor measurements.

Pollutant	CO	NO_2	PM_{10}	SO_2
No. of Performance Evaluations*	20	28	12	7

*Some resources address more than one pollutant of interest.

Sensor Performance

- This search category also contains field and laboratory performance targets used in ongoing domestic and international sensor evaluation programs:
  - South Coast Air Quality Management District (SCAQMD) Air Quality Sensor Performance Evaluation Center (AQ-SPEC)
  - International: China Ministry of Environmental Protection (MEP)
  - European Committee for Standardization (CEN), Working Group 42 (*under development*)
  - ASTM International Sensor Performance Specifications and Test Procedures (*under development*)

Field Performance Tests

- Field tests:
  - Characterize sensor performance under **ambient** conditions and allow for direct assessment of the sensor **precision**, **bias**, and **comparability** with the reference method.
  - Incorporate the effects of relative **humidity**, ambient **temperature**, **selectivity** (and chemical interferents) and **drift** of the sensor (if the field deployment is sufficiently long term).

Field Performance Tests

- All of the field test evaluations identified in the search used collocation with a reference/equivalent monitor to assess sensor performance:
  - Sensor(s) located at various distances (e.g., 1 m to 3 km) from a reference monitor.
  - Field deployment ranged from 48-hr to a few years.

- Limited information available regarding:
  - Sensor placement relative to the reference monitor beyond specifying sampling height and distance.
  - Considerations for avoiding inducement of turbulent conditions at the inlet to the sensor or reference monitor.

Field Performance Test Results

Parameter[a]	CO		NO_2	
	Sensor	FRM/FEM[b]	Sensor	FRM/FEM[b]
Correlation coefficient (R)	0.18 to 0.88	NA[c]	0.3 to 0.99	NA[c]
Coefficient of determination (R^2)	0.03 to 0.97		0.02 to 0.99	
Slope	7.99E-04 to 0.91		0.2 to 2.6	
Intercept	0.06 to 166 ppbv		3.8 to 16 ppbv	
RMSE	7.32-170.99 ppmv		9 to 30.3 ppbv	
Completeness	44 to 99%	>= 75% [d]	37 to 93%	>= 75% [d]

[a] The parameter data shown are for hourly sensor measurements and reflect out-of-the-box performance (i.e., sensor data not adjusted by field calibrations).

[b] EPA federal reference method (FRM) and federal equivalent method (FEM).

[c] The procedures in 40 CFR part 53 subpart C for assessing the comparability of a candidate gas FEM and an FRM use the maximum discrepancies (differences) between the candidate FEM and FRM measurements rather than linear regression.

[d]. Completeness criteria for design values is in appendices 40 CFR part 50

Field Performance Test Results

Parameter[a]	PM_{10}		SO_2	
	Sensor	FRM/FEM[b]	Sensor	FRM/FEM[b]
Correlation coefficient (R)	0.14 to 0.78	$\geq$ 0.97	0.3 to 0.99	NA[d]
Coefficient of determination (R^2)	0.02 to 0.91	NA[c]	0.02 to 0.99	
Slope	0.12 to 1.34	1 +/- 0.10	0.2 to 2.6	
Intercept	-1.6 to 5.6 µg/m^3	+/- 5 µg/m^3	3.8 to 16 ppbv	
RMSE	13.83-64.38 ppbv	NA	9 to 30.3 ppbv	
Completeness	47 to 93%	>= 75% [e]	37 to 93%	>= 75% [e]

[a] The parameter data shown are for hourly sensor measurements and reflect out-of-the-box performance (i.e., sensor data not adjusted by field calibrations).

[b] EPA federal reference method (FRM) and federal equivalent method (FEM). PM10 range 15-300 ug/m3

[c] The procedures in 40 CFR part 53 subpart C for assessing the comparability for candidate PM_{10} FEMs do not evaluate R^2.

[d] The procedures in 40 CFR part 53 subpart C for assessing the comparability of a candidate gas FEM and an FRM use the maximum discrepancies (differences) between the candidate FEM and FRM measurements rather than linear regression.

[e]. Completeness criteria for design values is in appendices 40 CFR part 50

Lab Performance Tests

- Lab tests allow for:
  - Control of conditions (e.g., temperature, relative humidity) and for quantification of specific sensor parameters that cannot be determined directly from field tests: Detection limit, Upper measurement range, Linearity over operating range, Selectivity, and Response time.
  - Evaluation of sensor drift and the influence on sensor performance of specific conditions encountered in the outdoor, ambient environment: Relative humidity, Sampling temperature, Chemical interferents, and PM composition.

Lab Performance Test Results

Parameter[a]	CO	NO_2	PM_{10}	SO_2
Correlation coefficient (R)	0.99	0.96 to 0.99	No data	No data
Coefficient of determination (R^2)	0.99	0.99	No data	No data
Slope	0.86	0.89 to 1.22	No data	No data
Intercept	0.07 ppbv	-1.02 to 5.5 ppbv	No data	No data
Detection limit	< 4 to 20 ppbv	< 1 to 6 ppbv	No data	No data

[a] The parameter data shown are for hourly sensor measurements and reflect out-of-the-box performance (i.e., sensor data not adjusted by lab calibrations).

Testing Methodologies

- This search category contains specific field and laboratory procedures for conducting sensor performance assessments including procedures identified in:
  - Peer-reviewed literature and other studies.
  - Ongoing domestic and international sensor evaluation programs.

Sensor Calibration

- Calibration includes initial deployment of the sensor and procedures for calibrating sensors during field deployment.
- Most of the resources focused on initial calibrations and typically included relative humidity and ambient temperature.
- Various techniques used to correct sensor field data:
  - Ordinary least squares regression.
  - Multiple linear regression.
  - Polynomial regression.
  - Machine learning/artificial intelligence.
- Transparency & Consistency is needed regarding the regression method used and which metrics are reported.

Thank you

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