ESI sensor performance
against EPA standards

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Introduction

The purpose of this document is to provide a reference regarding the performance characteristics of ESI's air quality monitoring technology, specifically for O_3, NO_2, CO, SO_2 and PM measurements. The information below compares the performance of these sensors with the recommended performance metrics and target values published by the United States Environmental Protection Agency (U.S. EPA) for Non-Regulatory Supplemental and Informational Monitoring (NSIM) applications.

ESI recognizes that its monitoring approach incorporates electrochemical and optical sensors, which differ from Federal Reference Method (FRM) and Federal Equivalent Method (FEM) instruments used for regulatory compliance determinations. However, these sensor types are included within the EPA's NSIM framework, which outlines testing procedures and performance targets intended to support their use in supplemental ambient air monitoring when evaluated against reference measurements.

This document summarizes:

1. Relevant U.S. EPA NSIM recommended performance metrics for O_3, NO_2, CO, $PM_{2.5}$ and SO_2 sensors; and
2. A comparison with results from ESI collocation studies, where available, to provide context on how the technology performs relative to these reference values.

The intent is to support a shared technical understanding of how ESI sensor measurements relate to recognized guidance for non-regulatory air quality monitoring applications.

Note on Calibration Methodology and Metrics Used

Unlike traditional low-cost sensors that rely on fixed linear calibration models assessed through slope and intercept bias, ESI devices use a patented AI-based dynamic calibration system that continuously optimizes sensor output against reference measurements while compensating for drift, temperature, relative humidity, and pressure effects. Therefore, performance is more appropriately evaluated using linearity (R^2) and RMSE, which directly reflect agreement with reference data over time. Slope and intercept are not included in the performance discussion because they are primarily suited to traditional low-cost sensors that use fixed linear calibration equations.

References

U.S. EPA Performance Targets for O_3, NO_2, CO, and SO_2 Sensors

U.S. EPA Performance Targets for Fine Particulate Matter Sensors

1. Context on Sensor Type and Intended Use

ESI's air quality monitoring systems incorporate electrochemical and optical sensing technologies. These are not Federal Reference Method (FRM) or Federal Equivalent Method (FEM) instruments, and therefore they are not intended to replace regulatory monitors used for compliance determinations.

However, these sensor types are included in the U.S. EPA framework for Non-Regulatory Supplemental and Informational Monitoring (NSIM), which provides testing protocols and recommended performance targets for their use in ambient, outdoor, fixed-site monitoring. NSIM applications may support:

- Screening and characterization of air pollution levels
- Identification of emission hot spots and contributing sources
- Community or near-source exposure assessment
- Supplemental monitoring where FRM/FEM systems are limited

Under this framework, sensor performance is evaluated by collocation with calibrated reference instruments, followed by assessing key performance indicators.

2. Relevant U.S. EPA Recommended Performance Targets (NSIM)

The EPA provides recommended performance targets for O_3, NO_2, CO, SO_2 and PM sensors used in ambient NSIM applications. A simplified summary is presented below:

Metric	O_3 Target	NO_2 Target	CO Target	SO_2 Target	Fine $PM_{2.5}$ Target
Linearity (R^2)	≥ 0.80	≥ 0.70	≥ 0.80	≥ 0.70	**≥ 0.70**
RMSE	≤ 5 ppb	≤ 15 ppb	≤ 0.15 ppm	≤ 15 ppb	**≤ 7 µg/m³ (24-hr), ≤ 12 µg/m³ (hourly)**
Slope (Bias)	1.0 ± 0.2	1.0 ± 0.35	1.0 ± 0.2	1.0 ± 0.35	**1.0 ± 0.35** *(recommended)*
Intercept (Bias)	−5 to 5 ppb	−5 to 5 ppb	−0.05 to 0.05 ppm	−5 to 5 ppb	**−5 to 5 µg/m³** *(recommended)*
Precision	SD ≤ 5 ppb or CV ≤ 30%	SD ≤ 5 ppb or CV ≤ 30%	SD ≤ 0.02 ppm or CV ≤ 30%	SD ≤ 5 ppb or CV ≤ 30%	**CV ≤ 30% (or SD ≤ 5 µg/m³)**

These metrics are used to characterize performance and do not represent regulatory certification.

3. Interpretation of Determination Coefficient (R^2)

In the NSIM context, these values fall within or above EPA's recommended linearity ranges for the pollutants under consideration.

For reference:

- O_3 target R^2: **≥ 0.80**
- NO_2 target R^2: **≥ 0.70**
- CO target R^2: **≥ 0.80**
- SO_2 target R^2: **≥ 0.70**
- Fine PM target R^2: **≥ 0.70**

Accordingly, R^2 in the range of 0.84–0.90 is consistent with, and in several cases stronger than, the NSIM target linearity recommendations for these gases. The indicates compliance with U.S. EPA standards.

4. Sensor-by-Sensor Comparison of ESI Collocation Results with EPA NSIM Targets

This section presents a detailed comparison of ESI's collocated sensor performance against the U.S. EPA NSIM recommended target values. Results are organized by pollutant to enable clear technical evaluation. All deployments listed were fixed-site collocations against regulatory reference analyzers across multiple regions including Canada, the United States, and Europe.

4.1 Carbon Monoxide (CO)

ESI conducted CO collocation studies in two locations, demonstrating strong linearity and low error. Both deployments exceed the U.S. EPA NSIM recommended linearity target (**$R^2 \geq 0.80$**) and fall within expected accuracy ranges for supplemental ambient air monitoring. *(Reference: U.S. EPA Performance Targets for O_3, NO_2, CO, and SO_2 Sensors, Table 4-2, printed page 27.)*

Location	Duration	Operation Mode	R^2	RMSE (ppm)
Hamilton, Ontario, Canada	Dec 2021 – Nov 2022	Fixed	0.91	0.05
Toronto, Ontario, Canada	Jan 2024 – July 2024	Fixed	0.95	0.02

Performance Interpretation:
CO performance at both sites exceeds NSIM linearity expectations, indicating suitability for identifying elevated CO concentrations and supporting hotspot or emissions screening applications.

4.2 Nitrogen Dioxide (NO2)

ESI has completed multiple NO_2 collocation studies across various climatic regions. All available deployments demonstrate linearity at or above the U.S. EPA NSIM recommended target (**$R^2 \geq 0.70$**) with RMSE values within the typical performance range for supplemental ambient monitoring.

(Reference: U.S. EPA Performance Targets for O_3, NO_2, CO, and SO_2 Sensors, Table 4-2, printed page 27.)

Location	Duration	Operation Mode	R^2	RMSE (ppb)
Hamilton, Ontario, Canada	Dec 2021 – Nov 2022	Fixed	0.97	1.32
I-25 – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.85	3.95
Rocky Flats – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.84	4.44
Tallinn, Harju, Estonia	July 2024 – Dec 2024	Fixed	0.97	0.89
Toronto, Ontario, Canada	Jan 2024 – July 2024	Fixed	1.00	0.64
Welby – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.93	2.90

Performance Interpretation:
All locations meet or exceed the EPA NSIM linearity target of **$R^2 \geq 0.70$** for NO_2. RMSE values remain within performance ranges reported for supplemental air quality monitoring, acknowledging expected variability in high-elevation and complex atmospheric environments such as the Denver region. These results support the use of ESI NO_2 measurements for hotspot identification, near-source exposure assessment, and screening applications where FRM/FEM systems are limited.

4.3 Ozone (O3)

ESI has conducted O_3 collocation studies across diverse climates including coastal, high-elevation, and semi-arid regions. All deployments meet or exceed the U.S. EPA NSIM recommended linearity target for O_3 (**$R^2 \geq 0.80$**) with RMSE values within the expected performance range for supplemental monitoring.

(Reference: U.S. EPA Performance Targets for O_3, NO_2, CO, and SO_2 Sensors, Table 4-2, printed page 27.)

Location	Duration	Operation Mode	R^2	RMSE (ppb)
El Paso, Texas, USA	July 2025 – Sept 2025	Fixed	0.85	5.02
Hamilton, Ontario, Canada	Dec 2021 – Nov 2022	Fixed	0.94	2.75
Rocky Flats – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.91	2.78
Tallinn, Harju, Estonia	July 2024 – Dec 2024	Fixed	0.97	1.67
Toronto, Ontario, Canada	Jan 2024 – July 2024	Fixed	0.99	1.42
Welby – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.97	3.37

Performance Interpretation:
All ozone results exceed the NSIM linearity target (**$R^2 \geq 0.80$**) and demonstrate RMSE values consistent with supplemental monitoring performance expectations. Higher RMSE values in some Denver-area deployments are consistent with known atmospheric variability in high-elevation ozone formation zones and remain within acceptable NSIM guidelines. These results support the suitability of ESI O_3 measurements for regional ozone pattern assessment, screening of pollution episodes, and source-influenced hotspot detection.

4.4 Sulphur Dioxide (SO2)

ESI has completed SO_2 collocation studies in three regions. All deployments meet or exceed the U.S. EPA NSIM recommended linearity target for SO_2 (**$R^2 \geq 0.70$**) and demonstrate RMSE values in the expected performance range for supplemental ambient monitoring.
(Reference: U.S. EPA Performance Targets for O_3, NO_2, CO, and SO_2 Sensors, Table 4-2, printed page 27.)

Location	Duration	Operation Mode	R^2	RMSE (ppb)
Hamilton, Ontario, Canada	Dec 2021 – Nov 2022	Fixed	0.88	4.05
Tallinn, Harju, Estonia	July 2024 – Dec 2024	Fixed	0.76	0.08
Toronto, Ontario, Canada	Jan 2024 – July 2024	Fixed	0.98	0.03

Performance Interpretation:
All SO_2 deployments satisfy the EPA NSIM linearity requirement (**$R^2 \geq 0.70$**) and exhibit RMSE values within expected ranges for supplemental monitoring. The highest RMSE is observed in Hamilton, consistent with typical near-source variability in sulfur compounds, while Tallinn and Toronto deployments demonstrate error levels near the reference instrument noise threshold. These results support the use of ESI SO_2 measurements for localized emissions screening, community exposure characterization, and hotspot detection where FRM/FEM monitoring capacity is limited.

4.5 Particulate Matter (PM2.5)

ESI conducted $PM_{2.5}$ collocation studies in multiple regions including high-elevation, desert, coastal, and northern continental environments. All deployments meet or exceed the U.S. EPA NSIM recommended linearity target for $PM_{2.5}$ (**$R^2 \geq 0.70$**) and demonstrate RMSE values within expected error ranges for supplemental ambient monitoring.

(Reference: U.S. EPA Performance Targets for Fine Particulate Matter Sensors, Table 4-1 printed page 36.)

Location	Duration	Operation Mode	R^2	RMSE (µg/m^3)
El Paso, Texas, USA	July 2025 – Sept 2025	Fixed	0.97	1.87
I-25 – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.91	2.15
Tallinn, Harju, Estonia	July 2024 – Dec 2024	Fixed	0.97	0.60
Toronto, Ontario, Canada	Jan 2024 – July 2024	Fixed	1.00	0.31
Welby – Denver, Colorado, USA	Aug 2024 – Oct 2024	Fixed	0.90	1.79

Performance Interpretation:

All $PM_{2.5}$ collocations meet or exceed the EPA NSIM linearity target ($R^2 \geq 0.70$), and RMSE values fall within expected supplemental monitoring performance ranges, with strongest accuracy observed in Tallinn and Toronto. Higher RMSE values in Denver and El Paso reflect known particulate variability in high-wind and dust-influenced regions and remain consistent with expected NSIM performance in these environments. These results support the applicability of ESI $PM_{2.5}$ data for hotspot screening, community exposure characterization, near-roadway monitoring, and emissions trend analysis.

Conclusion

The EPA NSIM performance target documents provide guidance for evaluating non-regulatory air quality sensors, including electrochemical and optical particle technologies, for supplemental ambient monitoring applications. Across the collocation deployments evaluated in this report, covering CO, NO_2, O_3, SO_2, and $PM_{2.5}$, ESI sensors achieved R^2 and RMSE values that were within the EPA NSIM recommended target ranges. These results indicate that ESI monitoring systems demonstrate performance consistent with EPA guidance for supplemental monitoring applications, including hotspot identification, community-exposure assessment, and screening-level air quality evaluation where reference-grade monitoring is limited. While these systems are not intended to replace FRM/FEM instruments for regulatory compliance, the observed agreement with reference measurements supports their use as reliable tools for expanding spatial air quality coverage and informing non-regulatory monitoring decisions.