COLORADO
Department of Transportation

CDOT Applied Research and Innovation Branch

Assessing the Suitability of Non-Regulatory Sensors for Particulate Matter Measurements in Transportation Applications

Katheryn R Kolesar

August 2024

Report No. CDOT-2024-09

Technical Report Documentation Page

1. Report No. CDOT-2024-09	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Assessing the Suitability of Non-Regulatory Sensors for Particulate Matter Measurements in Transportation Applications

5. Report Date
August 2024

6. Performing Organization Code

7. Author(s)
Katheryn R Kolesar, 0000-0002-9771-0708

8. Performing Organization Report No.

9. Performing Organization Name and Address
Air Sciences Inc.
150 Capital Dr., Ste. 320
Golden, CO 80401

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
R121.05

12. Sponsoring Agency Name and Address
Colorado Department of Transportation
Applied Research and Innovation Branch
2829 W. Howard Pl., Denver CO, 80204

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract

In 2020, the Colorado Department of Transportation (CDOT), in collaboration with the Colorado Department of Public Health & Environment (CDPHE) Air Pollution Control Division (APCD), began monitoring along a section of Interstate (I) 270 that is slated for roadway construction. Specifically, five types of non-regulatory supplemental and informational monitoring (NSIM) sensors were installed along a 4.5-mile section of I-270. Data and experience from this study were used to assess the suitability of NSIM sensors for measuring air quality impacts before, during, and after roadway construction projects. The accuracy of the NSIM sensors for measuring particulate matter (PM) less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) was assessed by determining overall average accuracy (linear fit of paired hourly data) and evaluating the accuracy near the 24-hour National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ (35 micrograms/meters^3). This study also includes information about the operations and maintenance required for each NSIM sensor.

Based on the comparisons in this study and information from previous studies, the 2B Tech AQSync and QuantAQ MODULAIR™-PM sensors were determined to be the most suitable for measuring PM during roadway construction projects. For applications requiring $PM_{2.5}$ and PM_{10} (PM less than 10 micrometers in aerodynamic diameter) monitoring, as well as an NSIM sensor that can be quickly set up and moved, the QuantAQ MODULAIR™-PM was found to be most suitable. For applications requiring the monitoring of a broader set of pollutants, the 2B Tech AQSync was found to be most suitable.

17. Keywords
Air quality, Environmental monitoring, Construction, Environmental impacts

18. Distribution Statement
This document is available on CDOT’s website https://www.codot.gov/programs/research

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 41	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgements

This research was funded by the Colorado Department of Transportation (CDOT), in collaboration with the Colorado Department of Public Health & Environment (CDPHE), under CDOT Contract No. 23-HTD-ZA-00038 and CDPHE Contract No. 2022*2820. Any opinions, findings, and conclusions or recommendations expressed in this material do not necessarily reflect the views of CDOT or CDPHE. The authors wish to thank CDOT personnel, including Stephen Cohn, Matthew Muraro, and Meteb Mejbel, and CDPHE personnel, including Tom Moore (now at the Regional Air Quality Council) and Gordon Pierce (retired), for their comments and input to guide the development of this project.

Table of Contents

Tables

Figures

Abbreviations

AQ-SPEC	Air Quality Sensor Performance Evaluation Center
CDOT	Colorado Department of Transportation
CDPHE	Colorado Department of Public Health & Environment
CRS	Colorado Revised Statute
DQO	Data Quality Objective
EPA	Environmental Protection Agency
FEM	Federal Equivalent Method
FRM	Federal Reference Method
I	Interstate
MCERTS	Monitoring Certification Scheme
$\mu g/m^3$	Micrograms per meter cubed
NAAQS	National Ambient Air Quality Standards
NSIM	Non-regulatory supplemental and informational monitoring
PM	Particulate matter
PM_1	Particulate matter with aerodynamic diameter < 1.0 µm
$PM_{2.5}$	Particulate matter with aerodynamic diameter < 2.5 µm
PM_{10}	Particulate matter with aerodynamic diameter < 10 µm
ppm	Parts per million
RS/TC	Regionally Significant and Transportation Capacity
SB	Senate Bill
SCAQMD	South Coast Air Quality Monitoring District
US	United States

Executive Summary

In 2020, the Colorado Department of Transportation (CDOT), in collaboration with the Colorado Department of Public Health & Environment (CDPHE) Air Pollution Control Division (APCD), began monitoring air quality along a section of Interstate 270 that is slated for roadway construction. Five types of non-regulatory supplemental and informational monitoring (NSIM) sensors were installed along a section of I-270 that spans 4.5 miles. As part of this study, eight sites were established. Data and observations from March to September 2023 are presented here as part of the investigation into the suitability of NSIM sensors for measuring air quality impacts before, during, and after roadway construction projects.

The main pollutants of interest during roadway construction projects are particulate matter with an aerodynamic diameter less than 2.5 micrometers ($PM_{2.5}$) and less than 10 micrometers (PM_{10}). Of the NSIM sensors deployed in this study, the 2B Tech AQSync, QuantAQ MODULAIR™-PM, and TSI Environmental DustTrak all have capabilities of measuring both $PM_{2.5}$ and PM_{10}. The Clarity Node-S and Lunar Outpost Canary-S may be suitable for applications that require only $PM_{2.5}$ measurements, but they are not suitable for applications that require PM_{10} measurements. While the Clarity Node-S and Lunar Outpost Canary-S both report data for PM_{10} measurements, these data are inaccurate and should not be used.

There is a wide range of accuracy in the measurements of pollutants made by NSIM sensors. Therefore, one component of this study investigated the accuracy of the NSIM sensors in measuring $PM_{2.5}$. This study did not assess the accuracy of measuring PM_{10} due to the lack of an acceptable PM_{10} standard to which the NSIM sensor measurements could be compared. $PM_{2.5}$ measurement accuracy was assessed by determining overall average accuracy (linear fit of paired hourly data) and evaluating the accuracy near the 24-hour National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ (35.4 micrograms/m^3). Based on the comparisons in this study and information from previous studies, the 2B Tech AQSync and QuantAQ MODULAIR™-PM sensors were determined to be the most suitable for measuring PM during roadway construction projects.

When choosing an NSIM sensor for use on a project, it is important to consider operational factors in addition to accuracy. Between the 2B Tech AQSync and the QuantAQ MODULAIR™-PM, the former takes the most effort to operate because it requires AC power and has a large footprint. A solar-powered trailer is available for the 2B Tech AQSync; however, compared with the solar panel for the QuantAQ MODULAIR™-PM, it is still much larger. The QuantAQ MODULAIR™-PM has a small footprint and can be mounted on a pole by one person. Therefore, for applications requiring $PM_{2.5}$ and PM_{10} monitoring—and an NSIM sensor that can be quickly set up and moved—the QuantAQ MODULAIR™-PM is most suitable. For applications requiring the monitoring of traffic-related air pollutants beyond PM (e.g., gaseous compounds), the 2B Tech AQSync is most suitable.

Implementation Statement

The information presented in this report has been used to inform the selection of NSIM sensors that are used for collecting measurements of $PM_{2.5}$ and PM_{10} during construction of planned Regionally Significant and Transportation Capacity (RS/TC) projects, as required under Colorado Revised Statute (CRS) 43-1-128. Specifically, the experience with operations and maintenance has been useful for informing:

- Selection of NSIM sensors to meet the requirements for PM monitoring, including best practices for evaluating the accuracy and precision of the NSIM sensors
- NSIM sensor siting along the planned RS/TC projects to capture potential impacts of construction emissions on nearby communities
- Limitations on the data uses and conclusions
- Setting expectations for the level of effort that would be needed for PM monitoring during planned RS/TC projects

Another potential implementation is the use of the accuracy assessment method presented here for CDOT to evaluate additional NSIM sensors for use during planned RS/TC construction projects. There are several other commercially available NSIM sensors capable of measuring $PM_{2.5}$ and PM_{10} that may also be suitable for CRS 43-1-128 compliance. CDOT could use the accuracy assessment method to evaluate these NSIM sensors for planned RS/TC projects and create a list of acceptable equipment. This list could then be used by individual regions to select a sensor for their projects.

As NSIM sensors have become more available and accurate, members of the public have started asking for additional information about the impacts of roadway construction projects and transportation on their communities. In response, departments of transportation have started supporting the collection and distribution of air quality information. However, as illustrated by the results of this study, the ease of operation and accuracy of measurements vary across the different NSIM sensors. Therefore, departments of transportation can use the quantitative and qualitative data presented in this report to inform their own air quality program development.

1.0 Introduction

In 2021, the Colorado Legislature passed Senate Bill (SB) 21-260: Sustainability of the Transportation System. This bill mandated, among other things, that the Colorado Department of Transportation (CDOT) measure air quality adjacent to planned Regionally Significant and Transportation Capacity (RS/TC) construction projects. Colorado Revised Statute (CRS) 43-1-128 codified these requirements.

There are two objectives for measurements that will be required for planned RS/TC projects. The first objective is to conduct monitoring prior to the start of construction to determine the concentrations of transportation related criteria air pollutants: carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), and particulate matter with an aerodynamic diameter less than 2.5 micrometers ($PM_{2.5}$) and less than 10 micrometers (PM_{10}). The second objective—the focus of this report—is to conduct monitoring for $PM_{2.5}$ and PM_{10} during construction to reduce the air quality impacts of construction on adjacent communities.

1.1 Background

Traffic-related air pollutants (TRAP) are a major contributor to urban air pollution. These pollutants are a complex mixture of airborne compounds that can be classified into two groups. The first is tailpipe emissions, such as nitrogen oxides (NOx, which includes both nitrogen oxide [NO] and NO_2), CO, $PM_{2.5}$, and hydrocarbons. The second is non-tailpipe emissions, which are predominantly PM_{10} that are caused by tire wear and the resuspension of road dust. Within the TRAP category, NO_2, CO, $PM_{2.5}$, and PM_{10} are all regulated under the National Ambient Air Quality Standards (NAAQS). In the Denver area, as with many cities in the United States (US), about 20 percent or greater of urban $PM_{2.5}$ can be attributed to on-road transportation (Li & Managi, 2021). PM from transportation sources includes primary emissions (i.e., black carbon, brake wear, tire wear, oil droplets) and secondary emissions (i.e., formation of PM downwind via atmospheric processing of hydrocarbons).

Numerous studies have found the concentration of TRAP is greatest downwind of highway areas and decreases with distance from the highway. In a study on the dispersion of ultrafine particulate matter (PM_1, PM with aerodynamic diameter less than 1 µm) particle concentration downwind from a major freeway in Los Angeles, concentrations were observed to decay to almost urban background levels by about 1,000 feet (300 meters) from the roadway (Zhu et al., 2002). For one study area along I-94 in Detroit, modeled $PM_{2.5}$ concentrations from roadway emissions decreased to only 10 to 25 percent of initial concentrations by 100 meters from the roadway (Isakov et al., 2014). Although there are differences in the measured rates of decay, it is well-established that communities adjacent to highways are disproportionately impacted by elevated concentrations of TRAP (e.g., Samuels & Freemark, 2022).

Additionally, there are emissions of TRAP associated with highway construction projects. Some activities that can lead to $PM_{2.5}$ and/or PM_{10} emissions include:

- Construction equipment combustion engines
- Generators
- Windblown dust from unpaved roadways, paved surfaces, and other unpaved/disturbed areas
- Changes to highway traffic patterns and volumes
- Asphalt paving
- Earth-moving activities
- Transportation of bulk materials
- Stockpiles

This list is based on CDOT staff members' knowledge, and it is supported by emissions factors and modeling available in the published literature (e.g., Perkinson, 1998; Muleski et al., 2005; Kinsey et al., 2004; Tanfeng et al., 2018). Despite the abundance of research to develop emissions factors on individual construction processes, as well as the modeling of construction emissions through scientific studies and the National Environmental Protection Act (NEPA), very few studies measure the changes to PM adjacent to roadway construction projects.

One study found that during a road-widening project in London, PM_{10} emissions increased by up to 15 $\mu g/m^3$ during working hours while the emission increases of other pollutants were negligible (Font et al., 2014). This study (Font et al. 2014) also found that after the road was widened, $PM_{2.5}$ and PM_{10} increased, which is contrary to other research findings of Harleman et al. (2023). These studies suggest construction-related emissions can further increase PM exposure in adjacent communities. However, more research is needed to develop a better understanding of what factors affect local air quality and what types of mitigation measures are effective. These are areas of study for several ongoing CDOT research projects.

One challenge with quantifying the impacts of highway construction emissions on adjacent communities has been the lack of suitable technology that can be deployed near the projects (i.e., within the right-of-way), to measure $PM_{2.5}$ and PM_{10}. To measure PM for regulatory purposes, governmental agencies use monitors that meet stringent criteria for performance and operation. These criteria are embodied in the Federal Reference Method (FRM) and Federal Equivalent Method (FEM) designations from the US Environmental Protection Agency (EPA). These monitors have defined accuracy tolerances and known capabilities. In addition, they are expensive, often require temperature-controlled enclosures, and must have access to line power or large solar power systems. These constraints make FEM/FRM monitors impractical to operate adjacent to most highway construction projects.

There is another category of instruments that do not meet EPA criteria for FRM or FEM. These instruments are referred to as non-regulatory supplemental and informational monitoring (NSIM) sensors by the EPA. NSIM sensors vary in performance, accuracy, power consumption, price, and ease of operation. Due to the operational flexibility they provide, NSIM sensors may provide the capabilities needed to gather information about the impact of highway construction activities on local air quality at the site and in adjacent communities.

1.2 CDOT Potential Applications

As part of CRS 43-1-128, there are two objectives for the PM measurement requirements during construction projects. First, there must be public alerts issued when PM concentrations reach the NAAQS thresholds for the corresponding 24-hour averages. Second, there must be an action plan to mitigate construction-related emissions contributing to poor air quality.

Since it is not practical to differentiate between sources of PM based on ambient measurements of particle mass concentration, having the measurements as close as possible to the highway is beneficial to linking measured PM concentration to construction activities. However, there is a trade-off in monitoring close to construction activities and the ability to understand impacts on communities if they are farther away from the project due to dispersion of the pollutants. Additionally, as construction activities move, it is desirable to also have the option of moving the PM measurements. Therefore, the most practical monitoring situation is to measure PM within the right-of-way and have a device that is easily relocated. When it comes to PM monitoring both before and during construction, the key constraints include:

- Power consumption and the ability to operate equipment on solar power or a single circuit of 110 V line power
- The footprint of the equipment
- The ability to mount the equipment on a pole or tripod
- The accuracy of the device (specifically, its ability to accurately measure one-hour and 24-hour average concentrations above and below the NAAQS)

The monitoring to be conducted prior to construction should also be conducted close to the highway to best capture the PM concentrations without interference from other sources of emissions.

Because of these constraints, NSIM sensors are an attractive option; they often require less power and have smaller footprints than FEM/FRM monitors. Further, many of these sensors are designed to be run on solar power. Several NSIM sensors have also been shown to be reasonably accurate, especially at 24-hour averages. However, not all NSIM sensors are suitable for the intended applications. This report includes an evaluation of several NSIM sensors, as well as a framework methodology for assessing NSIM sensors for use in CRS 43-1-128.

1.3 Project Objectives

In 2021, prior to the passage of SB 21-260, CDOT began a research study to better understand local air quality impacts of emissions from transportation and construction. The study area is along the I-270 corridor near Denver, Colorado. During the installation and operation of the research study, many lessons were learned about the suitability of specific NSIM sensors for making PM measurements in transportation research settings. This information was then applied to assessing the suitability of using NSIM sensors as part of the monitoring required during transportation construction projects under CRS 43-1-128. Specifically, CDOT is interested in knowing whether NSIM sensors are suitable for collecting reliable PM data that can be communicated to the public with confidence during construction of planned RS/TC projects.

This report aims to investigate the suitability of NSIM sensors for CRS 43-1-128 PM monitoring by investigating several questions:

1) What is the process for assessing the suitability of NSIM sensors for measuring transportation-related PM emissions?

2) What are important considerations for selecting NSIM sensors as part of PM monitoring required by CRS 43-1-128 for planned RS/TC projects?

3) Which types of NSIM sensors are suitable for measuring PM during roadway construction projects?

2.0 I-270 Research Study Methods

The initial air quality monitoring along I-270 occurred prior to the start of highway construction. This work included seven Clarity Node-S sensors and five Lunar Outpost Canary-S sensors, which were deployed along I-270 in March 2021. Subsequently, two TSI Environmental DustTrak sensors and two 2B Tech AQSync sensors were purchased and installed at two locations in October 2022. In March 2023, CDOT borrowed a QuantAQ MODULAIR™-PM to assess its capabilities alongside the other NSIM sensors. Figure 1 shows a map of the study area, with the locations of the NSIM sensors and nearby CDPHE-operated FEM monitors. In September 2022, one of the Clarity Node-S sensors was moved to the CDPHE Globeville site to provide continuous evaluation of $PM_{2.5}$ measurements. Table 1 provides a summary of the sensors, their installation location, and the date of installation.

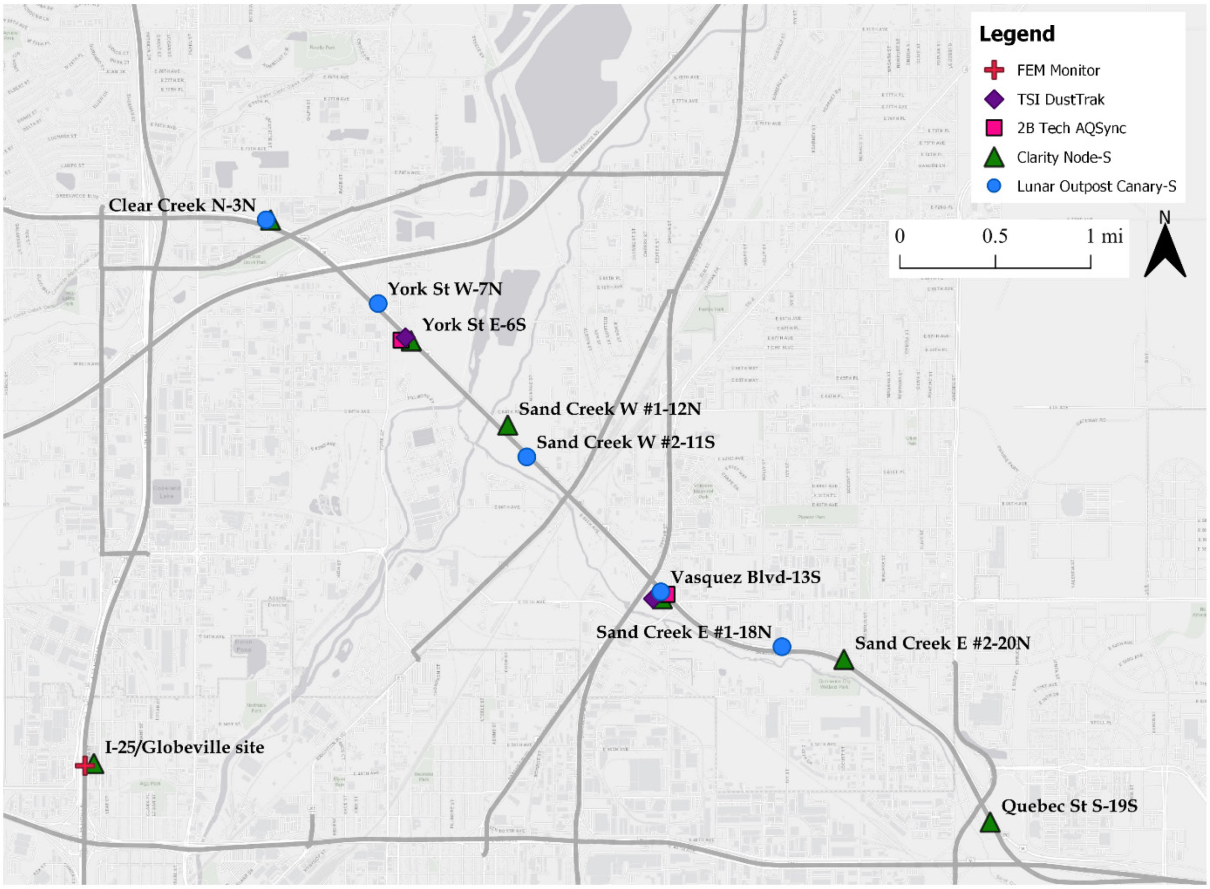

Figure 1. Map of the study area

Table 1. NSIM sensors installed along the I-270 corridor.

Manufacturer and model	Location	Dates of operation
Clarity Node-S	Clear Creek N-3N	Mar 19, 2021, to Aug 1, 2023
Clarity Node-S	York St E-6S	Mar 19, 2021, to Aug 1, 2023
Clarity Node-S	Sand Creek #2-11S	Mar 19, 2021, to Aug 1, 2023
Clarity Node-S	Vasquez Blvd-13S	Mar 19, 2021, to Aug 1, 2023
Clarity Node-S	Quebec St S-19S	Mar 19, 2021, to Aug 1, 2023
Clarity Node-S	Sand Creek #2-20N	Mar 19, 2021, to June 29, 2023
Clarity Node-S	Globeville (Collocated with the CDPHE FEM monitor)	Sept 8, 2022, to Aug 1, 2023
Lunar Outpost Canary-S	Clear Creek N-3N	Mar 19, 2021, to Aug 1, 2023
Lunar Outpost Canary-S	York St W-7N	Mar 19, 2021, to Aug 1, 2023
Lunar Outpost Canary-S	Sand Creek W #2-11S	Mar 19, 2021, to Aug 1, 2023
Lunar Outpost Canary-S	Vasquez Blvd-13S	Mar 19, 2021, to Aug 1, 2023
Lunar Outpost Canary-S	Sand Creek #1-18N	Mar 19, 2021, to Aug 1, 2023
2B Tech AQSync	York St E-6S	Oct 23, 2022 to Aug 1, 2023
2B Tech AQSync	Vasquez Blvd-13S	Oct 23, 2022 to Aug 1, 2023
TSI Environmental DustTrak	York St E-6S	Oct 19, 2022 to Aug 1, 2023
TSI Environmental DustTrak	Vasquez Blvd-13S	Nov 2, 2022 to Aug 1, 2023
Quant-AQ MODULAIR™-PM	York St E-6S	Feb 17, 2023 to Mar 17, 2023

Prior to the installation of the Clarity Node-S and Lunar Outpost Canary-S sensors along the I-270 corridor, they were collocated with FEM monitors at the CDPHE Globeville site from February 12, 2021, through March 18, 2021. The period of performance for this study is from November 1, 2022, through August 1, 2023. This is the period over which most of the sensors were installed along the I-270 corridor, and a Clarity Node-S was collocated with the FEM monitor at the CDPHE Globeville site. While many of the sensors were installed along the project through 2024, several were moved between August 1, 2023, and March 1, 2024.

2.1 General NSIM Sensor Assessment

The suitability of NSIM sensors for use by CDOT in measuring PM during transportation construction projects depends on several criteria:

- Accuracy (addressed in detail for $PM_{2.5}$ in Sections 3.2 to 3.5)
- Power requirements
- Data transmission capabilities
- Percent data capture
- Data resolution
- User experience notes

These criteria consider the intended uses of the NSIM sensors for CRS 43-1-128 compliance. For other applications, these criteria may need to be redefined.

Each criterion will be discussed as it applies to the deployed NSIM sensors. The sources of information for this section are published literature, experience with the NSIM sensors during the research study, and manufacturer recommendations.

2.2 Development of a Standard Measurement

In the EPA's *Enhanced Sensor Guidebook* (Clements et al., 2022), one recommended method for improving the accuracy of measurements made by an NSIM sensor network is a collocation strategy called continuous subset. With this method all NSIM sensors are first collocated with an FEM/FRM monitor, then a subset of NSIM sensors is continuously operated next to an FEM/FRM monitor while the other sensors are deployed elsewhere. The measurements from the collocated NSIM sensor are then compared in real time to the FEM monitor measurements, and adjustments are made based on the relationship. The same adjustments are then made to the deployed NSIM sensors in the network.

Throughout this study, one Clarity Node-S was collocated at the Globeville site, which includes an FEM monitor for $PM_{2.5}$. The Clarity Node-S was used for the continuous subset adjustment method. The process for adjusting the measurements from the Clarity Node-S is described below.

First, for each hour, a scaling factor was determined based on the ratio between the $PM_{2.5}$ measurements from the FEM at Globeville and the Clarity Node-S at Globeville. This is referred to as the hourly-specific scaling factor. Then, for each hour the hourly $PM_{2.5}$ Clarity Node-S measurement from the sensors deployed along I-270 was multiplied by the hourly specific scaling factor to obtain the hourly standard $PM_{2.5}$ value. These hourly standard $PM_{2.5}$ values were the basis for comparison with $PM_{2.5}$ measurements from other NSIM sensors in the I-270 research project. For each site, the Clarity Node-S sensor was referred to as the Clarity transfer standard.

Note that this method of developing a standard for the network may not always be possible. For each project, the appropriate data adjustment protocols, as outlined in the EPA's *Enhanced Sensor Guidebook* (Clements et al., 2022), should be identified.

2.3 Accuracy Assessment

The accuracy of many NSIM sensors depends on local conditions (composition and size of PM, temperature, relative humidity, wind speed, etc.), as well as sensor performance. To assess the accuracy of the NSIM sensors deployed along I-270, it is necessary to identify the metrics for evaluation. This study uses an EPA report about data quality objectives (DQOs) and performance testing protocols for NSIM sensor measurements of $PM_{2.5}$ (Duvall et al., 2021). The EPA does not have a similar publication for PM_{10}. The EPA report outlines proper testing and evaluation procedures for each type of NSIM sensor. It also recommends performance metrics and target values, which are summarized in Table 2. Note that $PM_{2.5}$ comparisons are conducted based on 24-hour averages. The guidance includes additional recommended performance metrics for the effects of temperature and relative humidity (RH), measurement drift, and accuracy at high concentrations.

Table 2. EPA performance metrics and target values for NSIM sensor measurements

Type	Performance metric	Target values
Precision	Standard deviation (SD) or coefficient of variation (CV)	≤ 5 µg/m3, or ≤ 30%
Bias	Slope (m)	1.0 ± 0.35
Bias	Intercept (b)	$-5 \leq b \leq 5$ µg/m3
Linearity	Coefficient of determination (R^2)	≥ 0.70
Error	Root mean square error (RMSE) or normalized RMSE (NRMSE)	RMSE ≤ 7 µg/m3 or NRMSE ≤ 30%

2.4 Evaluation of Event Detection

To meet the purpose and spirit of CRS 43-1-128, it is important to measure $PM_{2.5}$ during construction accurately enough to detect two different types of events.

The first type of event is an exceedance of the 24-hour NAAQS value of 35 µg/m^3. The implementation of CRS 43-1-128 requires that public notification be issued if this event occurs. Therefore, it is most important for the NSIM sensors to have reasonable accuracy for 24-hour averages measured near this threshold value.

The second event is when the hourly average $PM_{2.5}$ concentration exceeds 35 µg/m^3 for several hours (within a range of hours as determined appropriate for the project). The implementation of CRS 43-1-128 air quality monitoring requires that notifications be sent to the project construction teams if this event occurs. The purpose of the internal alert event is to help identify degradation in air quality and assess when mitigation is needed to prevent the 24-hour average from exceeding the NAAQS threshold. Therefore, one-hour accuracy near 35 µg/m^3 is important to avoid unnecessary internal alerts—and to ensure alerts are sent when necessary.

3.0 Results

The results of this study are presented in four sections:

1. A general NSIM sensor assessment that provides an overview of performance and ease of operation.
2. An evaluation of a “transfer standard” through the continuous subset method application.
3. The results of the accuracy assessment for each sensor in comparison to the Clarity transfer standard.
4. An evaluation of event detection for the purpose of CRS 43-1-128 compliance.

3.1 General NSIM Sensor Assessment

3.1.1 User Experience

All the NSIM sensors evaluated in this research project have unique characteristics, design, and manufacturers, which contribute to the user experience. The following sections summarize relevant information about the user experience from the past two years of the study. Many of the NSIM sensors are newer to the market, and several of the companies have started within the past five to 10 years, so the situations described here may change in the coming years.

3.1.1.1 Clarity Node-S

The Clarity Node-S is easy to install and comes with preconfigured telemetry to transmit data to the user’s account as soon as they power the unit. This is mostly an advantage; however, users should take care to document installation times and locations to attribute the data appropriately. For example, if a user turns on the unit in an office or home for testing before deployment, the Clarity database provides no way to differentiate these data from the field data.

Clarity recommends a two-week collocation with an FEM/FRM monitor prior to remote deployment. If this is possible, Clarity can help develop a calibration model that should improve data accuracy. The Clarity scientists can also provide helpful information about the model factors and the results so that users have choices, if they would like. The model itself is proprietary.

If a Clarity Node-S must be replaced, it can take two to three weeks as the replacements are shipped from the factory in Taiwan. Additionally, the Clarity database does not automatically provide alerts for malfunctioning sensors, so users should review the data routinely to identify anomalies.

Clarity is currently upgrading its application programming interface (API), and there have been several bumps in transitioning from v1 to v2. Part of the challenge is that the API information is available on the webpage, yet there is no distribution list to inform API users of changes. However, because all the data are stored in the Clarity database, no data are lost during this process.

Data download from the Clarity website is straightforward. The time column is clearly marked as Coordinated Universal Time (UTC); however, the averaging convention (time-beginning) is not stated. The download can be configured to include multiple sensors and even include data from FEM monitors that are pulled into the Clarity database. Data for each sensor are associated with a column that includes the device serial number. Attention must be paid when using the data, as there are several columns for $PM_{2.5}$. The columns are uncorrected data, calibrated data, and sometimes a number concentration. Since the column names are long, users can easily overlook this information.

3.1.1.2 Lunar Outpost Canary-S

The Lunar Outpost Canary-S is easy to install and comes with preconfigured telemetry to transmit data to the user's account as soon as they power the unit. As with the Clarity Node-S, this is mostly an advantage; however, users should be sure to note installation times and locations to attribute the data appropriately.

The Lunar Outpost Canary-S comes with a preset calibration, as the measurements from the $PM_{2.5}$ sensor agree very well with the FEM monitor data. The calibration model is proprietary, and there is no information about how the uncorrected measurements are manipulated.

If replacement parts are necessary for the telemetry, solar panel, power, or $PM_{2.5}$ measurements, repair is quick. This rapid repair was facilitated by the proximity of the Outpost Environmental office to the research project so there were no shipping times.

Data download from the website is straightforward. However, users must download data from one sensor at a time, and the name of the sensor on the website is not located anywhere in the downloaded file. Additionally, the time zone associated with the downloaded data is not readily apparent (it is UTC), and the time averaging convention (time-beginning) is not given.

The hourly averages are also not always associated with a time stamp at the bottom of the hour (minutes = 0). Instead, time stamps are at one to three minutes after the hour. This is different for each sensor, which requires manipulation of the time series to match up the data from different sensors. The data file also contains 15 to 20 extraneous columns that contain no information as the columns appear to be for sensors that are not part of the current Lunar Outpost Canary-S configuration.

3.1.1.3 QuantAQ MODULAIR™-PM

The QuantAQ MODULAIR™-PM is easy to install and comes with preconfigured telemetry to transmit data to the user's account as soon as the unit is powered on. As with the Clarity Node-S and Lunar Outpost Canary-S sensors, this is mostly an advantage; however, users should be sure to note installation times and locations to attribute the data appropriately.

The QuantAQ MODULAIR™-PM comes with preset calibrations that are available through the developer platform, which is available by request through the user account. QuantAQ is dedicated to publishing open-source information and will provide additional resources as requested so its calibration can be transparent and understood.

The QuantAQ MODULAIR™-PM typically ships from Massachusetts, which makes replacement of malfunctioning sensors possible within two to three days. The QuantAQ MODULAIR™-PM database does not automatically provide alerts for malfunctioning sensors, so users should review the data routinely to identify anomalies.

Data download from the website is straightforward. There are options to download data with various averaging periods, and documentation about the averaging techniques is available on the website. Within the data file, the start and end times are clearly stated in both UTC and sensor local time. As with EPA requirements, the averages calculated for the data download must meet a 75 percent data recovery requirement. This is not implemented with any of the other sensor platforms for data averaging. The data file is clean and easy to use.

In addition, the scientists at Quant-AQ have many years of experience with air quality research and instrumentation. They are deeply knowledgeable and happy to answer questions.

3.1.1.4 TSI Environmental DustTrak

The TSI Environmental DustTrak requires line power to install, and it is more difficult to set up than the Clarity Node-S, Lunar Outpost Canary-S, and QuantAQ MODULAIR™-PM. The modem (Thiamis by AirThinx) in the TSI Environmental DustTrak requires access to Environet, which has a yearly subscription. TSI managed the subscription at the beginning of this research project but it was recently switched over to AirThinx. Users were notified of this change via just one email and with only two weeks' notice. When setting up the modem in Environet, the user must also configure the TSI Environmental DustTrak and, if included, the Lufft meteorological station. This is a step that can easily be missed. Because the AirThinx modem does not store the data locally, failure to configure both the DustTrak and Lufft modules can result in lost data. It is also recommended that one-minute data be transmitted to Environet, as the averaging for wind direction is not performed according to EPA recommendations.

Quality checks of the TSI Environmental DustTrak and Lufft meteorological instruments are straightforward. Collocated National Institute of Standards and Technology (NIST) traceable standards for temperature and relative humidity are used to verify sensor accuracy. Because the wind direction and speed are measured using a sonic anemometer, verification needs to be done with a collocated standard or by sending the sonic anemometer to a laboratory. The flow rate for the TSI Environmental DustTrak is checked with a standard flow meter.

The original Thiamis modem purchased in 2022 was a 2G/3G modem. As of December 31, 2023, it was no longer supported, so a replacement 4G modem was purchased. If purchasing a TSI Environmental DustTrak from TSI, users should request the 4G modem.

During this study, the TSI Environmental DustTrak malfunctioned numerous times. One of these issues took over a month to resolve due to inconsistent troubleshooting support from TSI. The TSI Environmental DustTrak was purchased with a service plan; however, it has been the experience of this research project that this has been of limited usefulness for ensuring the sensors were working.

In contrast, customer support for the Thiamis modem by AirThinx was very prompt. The few issues that occurred were resolved in a few hours.

3.1.1.5 2B Tech AQSync

The 2B Tech AQSync sensors used on this research project were some of the first commercially purchased AQSyncs. In the first few months of operation, there were data losses due to issues with telemetry and data logging. These issues were resolved, and 2B Tech collaborated with the study team to ensure data-processing needs were met.

The 2B Tech AQSync was more challenging to install than the Lunar Outpost Canary-S, Clarity Node-S, or QuantAQ MODULAIR™-PM. It was also the largest of the NSIM sensors used in this research project and it measures more pollutants than just $PM_{2.5}$ and PM_{10}. A bucket truck or two people on a raised platform are necessary for installation. The default cable and attachment location for the meteorological module are not far enough away from the 2B Tech AQSync if it is mounted to a pole, which creates an obstruction for correctly measuring wind direction.

Quality checks and calibration of the 2B Tech AQSync are recommended for the PM module. During this study, the PM module quality checks and calibrations were straightforward, and the PM module flow rate was checked with a standard flow meter.

Data downloads from the website are straightforward and available at various averaging intervals. The start and end dates and times of the averaging period are clearly labeled, as is the time zone (UTC).

Module replacements for malfunctioning sensors were available within a few days. The 2B Tech office is in Colorado, which also reduced the wait time for this research project. All the 2B Tech scientists have a wealth of knowledge about air quality measurements and monitoring. They are also interested in sharing their knowledge and willing to troubleshoot issues as they arise.

3.1.2 Pollutants Measured

To comply with CRS 43-1-128, measurements of both $PM_{2.5}$ and PM_{10} must be reported to a public dashboard. The effective particle size ranges that each NSIM sensor measures are listed below.

- Clarity Node-S: 0.30 to 1 µm
- Lunar Outpost Canary-S: 0.30 to 1 µm
- 2B Tech AQSync: 0.30 to 10 µm
- TSI Environmental DustTrak: 0.50 to 10 µm
- QuantAQ MODULAIR™-PM: 0.35 to 40 µm

Information about the effective particle size ranges for the Clarity Node-S and Lunar Outpost Canary-S are from a 2023 study by Rueda et al. The lower end of the effective particle size range for the TSI Environmental DustTrak is based on a technical note of impactor penetration efficiency curves (TSI Incorporated, 2012). This technical note provides characterization for only 0.5-µm-diameter particles and larger. The effective particle size ranges of the other NSIM sensors are based on manufacturer specifications.

3.1.2.1 $PM_{2.5}$

Each NSIM sensor used in the current study reports $PM_{2.5}$ mass concentrations. Figure 2 shows example time series of the $PM_{2.5}$ measurements from the 2B Tech AQSync, TSI Environmental DustTrak, Lunar Outpost Canary-S, and Clarity Node-S (uncorrected data) for March 1–31, 2023. Note that Clarity Node-S data calibrated using the Clarity transfer standard method are shown in Figure 5.

For comparison, data are shown from two CDPHE FEM monitors: Adams-Birch and Globeville. Figure 2 also shows the reference point of the $PM_{2.5}$ 24-hour NAAQS, which is 35 $\mu g/m^3$. Note that this is the value when the data are rounded to the nearest 1 $\mu g/m^3$, according to rules described in Appendix N, Part 4.3, of Title 40, Section 50 of the Code of Federal Regulations. However, for the data analysis portion, the threshold event value is 35.4 $\mu g/m^3$, which is the highest possible value for the 24-hour average when rounding to the nearest 0.1 $\mu g/m^3$.

These plots are best for visually assessing how well the NSIM sensor measurements agree with the nearby FEM monitor measurements. If the FEM monitor traces are difficult to see, it is because the NSIM sensor measurements are similar. If the FEM monitor traces are clearly visible, it is because the NSIM sensor measurements are different.

Based on a visual assessment of the time series, the Clarity Node-S and TSI Environmental DustTrak both overestimate the $PM_{2.5}$, and the 2B Tech AQSync and Lunar Outpost Canary-S agree with the FEM monitor measurements quite well. The exception is for a $PM_{2.5}$ event on March 31, 2023, when both the Lunar Outpost Canary-S and Clarity Node-S underestimated the $PM_{2.5}$ by an order of magnitude.

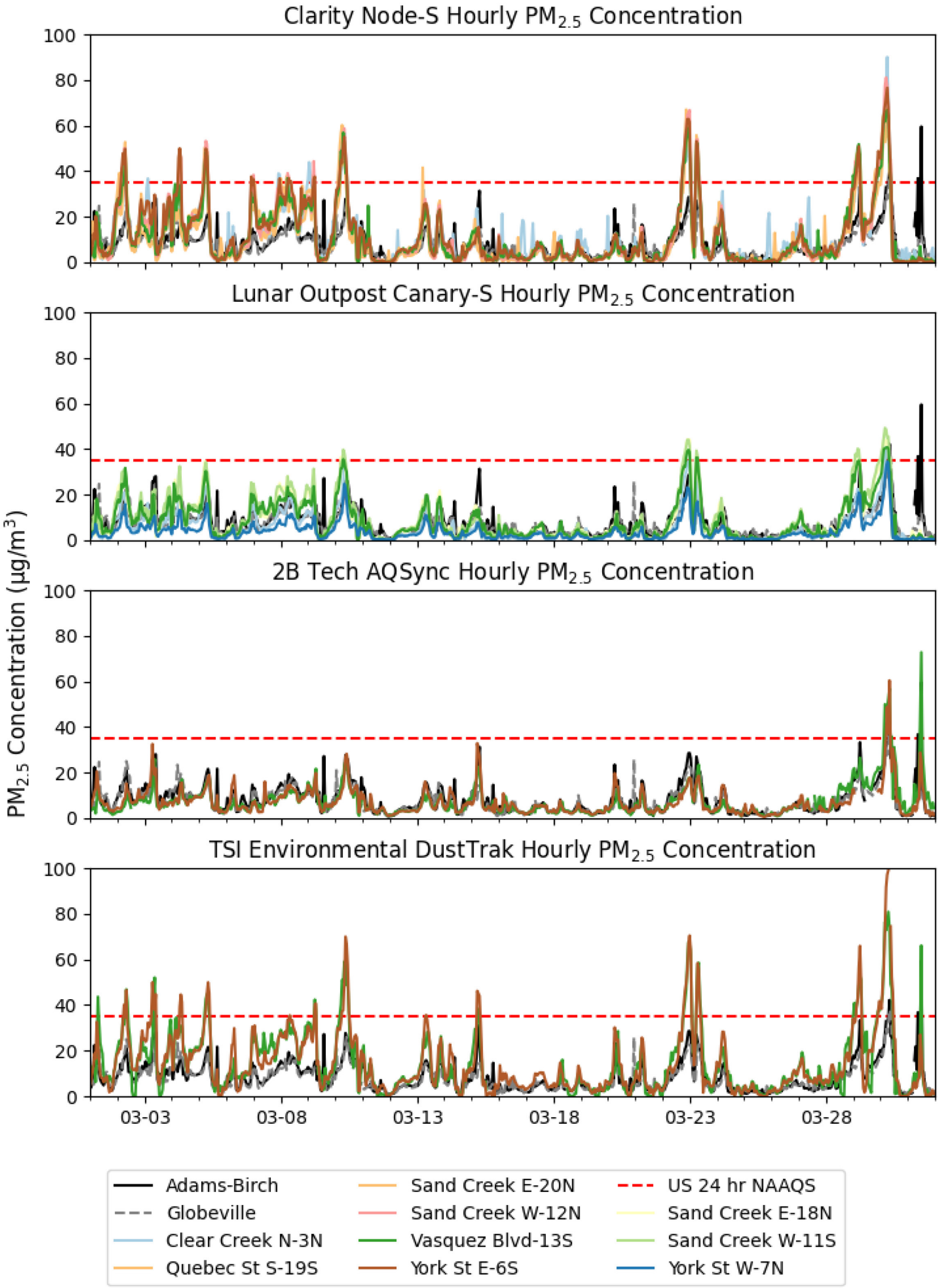

Figure 2. Time series of $PM_{2.5}$ measurements from March 1 to 31, 2023

3.1.2.2 PM_{10}

Many NSIM sensors claim to measure PM_{10}, yet many of these measurements are highly unreliable. Rueda et al. (2023) concluded that the PM_{10} signal from the PMS5003, which is used in the Clarity Node-S and Lunar Outpost Canary-S sensors, should be disregarded because it appears to provide no meaningful output. This is the consensus in the scientific community for any NSIM sensors that use a Plantower sensor (such as the PMS5003) or a similar sensor (e.g., Sensirion, Piera) for PM_{10} measurements. Nevertheless, commercial producers of NSIM sensors, including the Clarity Node-S and Lunar Outpost Canary-S, still make PM_{10} measurements available to users.

The 2B Tech AQSync, TSI Environmental DustTrak, and QuantAQ MODULAIR™-PM all use optical particle counters that are capable of reliably measuring PM_{10}. Figure 3 shows example time series of the 2B Tech AQSync and TSI Environmental DustTrak measurements for March 1 to 31, 2023 are shown in Figure 4. Data from the nearby Welby CDPHE FEM monitor are provided for comparison; however, local emissions of PM_{10} can have a substantial impact on the local measurements. It is important to note that the 2B Tech AQSync captured the regional PM event on March 31, but the TSI Environmental DustTrak (which seems to underestimate the amount of PM_{10}) did not.

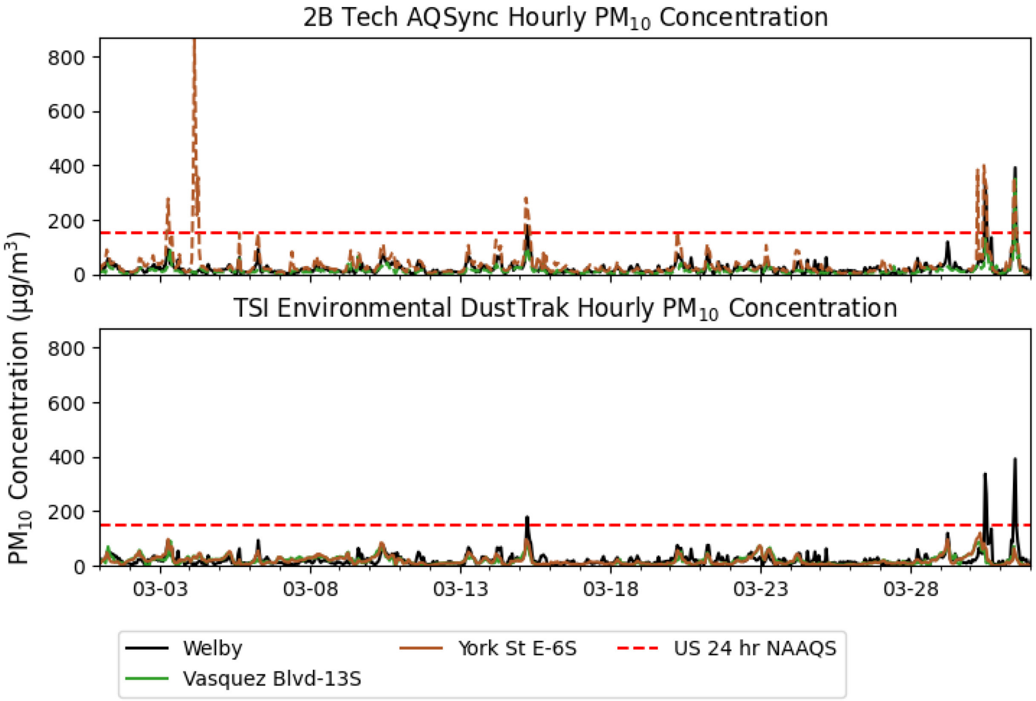

Figure 3. Time series of PM_{10} measurements from March 1 to 31, 2023

The 2B Tech AQSync at York St had two hours of PM_{10} measurements higher than 500 µg/m^3 that were not observed by the collocated TSI Environmental DustTrak or the other sensors. Additionally, there were a few hours of higher measured PM_{10} compared with the nearby FEM monitors and the TSI Environmental DustTrak. These could be due to small dust plumes that intersected the inlet of the 2B Tech AQSync and not the inlet of the TSI Environmental DustTrak. Potential causes of such a plume include someone driving on the berm of the highway or a truck laden with something dusty driving by the site. Alternatively, it could mean that the TSI Environmental DustTrak does not measure PM_{10} as efficiently as the 2B Tech AQSync.

3.1.2.3 Other PM measurements

While not a requirement of CRS 43-1-128, it is often useful to measure PM_1 (PM less than 1 µm in aerodynamic diameter) because typical diesel emissions are dominated by particles with a diameter less than 0.30 µm (Kittelson, 1998). The measurements discussed so far in this report are mass concentrations with units of $\mu g/m^3$, which are more influenced by the largest particles within each of $PM_{2.5}$ (close to 2.5 µm) or PM_{10} (close to 10µm). Since PM emitted directly from a tailpipe or construction activities, such as asphalt paving, is typically less than 1 µm in diameter, the increase in concentration of these particles is difficult to detect when looking at the total mass concentration (i.e., $\mu g/m^3$). However, it is also possible to measure the number concentration (in units of $\#/m^3$) of particles. This can be more favorable for detecting changes in ambient air quality due to emissions from construction activities. Of the NSIM sensors in this study, the QuantAQ MODULAIR™-PM is the only one that reports number concentration.

3.1.3 Data Validation and Review

Data collected on-site should be reviewed by a trained air quality scientist. This is best done graphically and by comparing parameters measured between nearby locations. Each NSIM sensor has an accompanying web-based platform developed by the manufacturer that allows for graphic representations of the data. Only the Clarity platform allows for the importation of data from regulatory monitors, which, for this study, were operated by CDPHE. The Lunar Outpost Canary-S, TSI Environmental DustTrak, and Clarity Node-S platforms allow for the creation of graphical displays of data from multiple sensors; however, for the Lunar Outpost Canary-S and Clarity Node-S, these must be configured with each browser session. The TSI Environmental DustTrak platform (Environet) allows users to create customizable dashboards. The settings for these dashboards are stored in the platform for quick access.

After data review, it is sometimes necessary to flag data as invalid, or valid but with a qualifying statement. This is an established practice with air quality data, and the EPA has established Air Quality System qualifier codes for flagging due to specific reasons. None of the manufacturer platforms allow the user to flag data to create a final, quality-checked dataset.

3.1.4 Data Capture

It is important to have an NSIM sensor that will reliably collect and transmit data to a web-based platform for automated retrieval. The ability of each NSIM sensor to do so was assessed by the percentage of hours for which valid data were captured. It is important to note that the valid data do not include hours that were flagged in the dataset as invalid for reasons such as site visits, calibration, or malfunction. The data capture summary and location for each NSIM sensor are given in Table 3. For information about the length of time the sensors were deployed, please refer to Table 1.

Table 3. Percentage of hours with valid measurements for each NSIM sensor

Manufacturer and sensor	Location	Data capture (%)
2B Tech AQSync	York St 6S	81.3
2B Tech AQSync	Vasquez Blvd 13S	80.8
TSI Environmental DustTrak	York St 6S	99.6
TSI Environmental DustTrak	Vasquez Blvd 13S	67.7
Lunar Outpost Canary-S	Clear Creek N 3N	92.3
Lunar Outpost Canary-S	York St W 7N	99.9
Lunar Outpost Canary-S	Sand Creek W 11S	98.7
Lunar Outpost Canary-S	Vasquez Blvd 13S	99.8
Lunar Outpost Canary-S	Sand Creek E 18N	99.6
Clarity Node-S	Clear Creek N 3N	98.9
Clarity Node-S	York St 6S	99.3
Clarity Node-S	Sand Creek W 12N	99.2
Clarity Node-S	Vasquez Blvd 13S	99.3
Clarity Node-S	Quebec St S 19S	99.3
Clarity Node-S	Sand Creek E 20N	87.2
Clarity Node-S	Globeville	99.7
QuantAQ MODULAIR™-PM	York St 6S	100.0
FEM	Globeville	93.8

Table 4 shows the data reliability for each type of sensor, summarized by the average data capture and standard deviation.

Table 4. Summary of percentage of hours with valid measurements for each NSIM sensor type

Manufacturer and sensor	Average data capture (%)	Standard deviation (%)
2B Tech AQSync	81.1	0.4
TSI Environmental DustTrak	83.7	22.6
Lunar Outpost Canary-S	98.1	3.3
Clarity Node-S	98.0	4.6
QuantAQ MODULAIR™-PM	100.00	--
FEM	93.8	--

3.1.5 Data Resolution

The NAAQS are evaluated based on 24-hour, eight-hour, one-hour, and annual averages. However, ambient air quality events often occur on shorter timescales. Therefore, to gain a better understanding of the effect of transportation and transportation construction on air quality, it is important to collect measurements that match the timescale of potential events. The maximum data resolution for each type of NSIM sensor is listed below.

- 2B Tech AQSync: 5 minutes
- TSI Environmental DustTrak: 1 minute
- Lunar Outpost Canary-S: 1 minute
- QuantAQ MODULAIR™-PM: 1 minute
- Clarity Node-S: ~ 7.5 minutes

The TSI Environmental DustTrak data resolution is customizable on the Environet platform. However, it is recommended to use one-minute resolution for data collection because the current version of the Thiamis data logger computes arithmetic averages for all parameters, including wind direction—which may not be desirable for specific applications.

The Clarity Node-S data resolution is not consistent between each subsequent measurement, and the start and end of the time interval is not standard between sensors. The time steps in the datasets ranged from 7 minutes, 28.4 seconds to 16 minutes, 4.34 seconds. This makes it extremely difficult to compare sub-hourly data between Clarity Node-S sensors and other types of sensors.

3.1.6 Data Transfer

It is often desirable to automate data transfer from a manufacturer's web-based database to another database. As part of the public reporting requirements of CRS 43-1-128, CDOT must aggregate the monitoring data and store the data in a departmental database.

It is possible to retrieve data from the Clarity Node-S, 2B Tech AQSync, QuantAQ MODULAIR™-PM, and TSI Environmental DustTrak web-based databases using an API. This is a straightforward and well-known method of retrieving data. The documentation for each API is available from the manufacturers. Clarity is currently transitioning from v1 to v2 for several products through the API. This transition has caused issues, as the timing of the deprecation of v1 has not been advertised. The Lunar Outpost online database does not have an associated API for data retrieval. It is possible to retrieve data using webhooks.

3.2 Development of the Clarity Transfer Standard

Use of the Clarity Node-S as a transfer standard depends on the use of the continuous subset adjustment method, which is one of many possible methods for improving the accuracy of NSIM sensor measurements. Other recommended methods are described in the EPA's *Enhanced Sensor Guidebook* (Clements et al., 2022). The Clarity Node-S continuous subset method was chosen for this research study because of its simplicity and likelihood to be accurate based on the proximity of the collocated sensor to the project.

From September 8, 2022, through May 31, 2023, a Clarity Node-S sensor was collocated with the CDPHE Globeville FEM monitor. The hourly $PM_{2.5}$ concentration measured by the Clarity Node-S unit is compared to the Globeville FEM monitor in Figure 4. The comparison between the Clarity Node-S unit and the Globeville FEM monitor shows that the Clarity Node-S had a relatively strong correlation with the FEM monitor measurements ($R^2 = 0.79$). The strong correlation indicates that once corrected, based on a site-specific slope and intercept, there is reasonable confidence the Clarity Node-S sensor will provide more accurate measurements. The Clarity Node-S did overestimate the $PM_{2.5}$ concentration by around 70 percent, on average (slope = 1.73, y-intercept = -1.88), which indicates adjustment is needed.

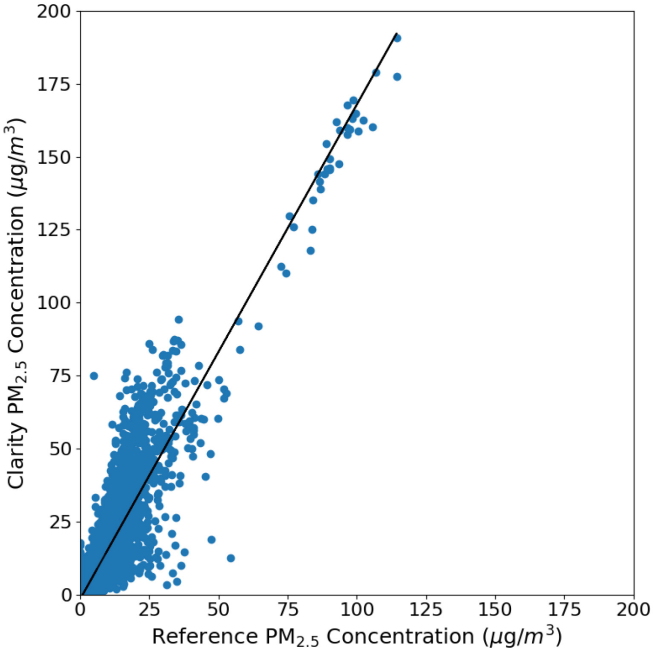

Figure 4. Comparison of the Clarity Node-S to the CDPHE Globeville FEM monitor for measurement of $PM_{2.5}$ concentration (September 8, 2022–May 31, 2023)

The first step in the application of the Clarity Node-S transfer standard was to determine how well measurements from the transfer standard agreed with the Globeville FEM monitor that was used to develop the scaling factors. Figure 5 shows the time series of the uncorrected Clarity Node-S $PM_{2.5}$ measurements from March 2023 alongside the Clarity Node-S $PM_{2.5}$ measurements after scaling. The scaled $PM_{2.5}$ measurements, which are shown in the bottom graph, are used as the Clarity transfer standard at each respective location.

As expected, this scaling led to better agreement between the Clarity Node-S measurements and the Globeville FEM monitor measurements. However, it also highlights how this approach may still miss local events, such as the dust event on March 31, 2023, which was detected by the 2B Tech AQSync, the TSI Environmental DustTrak, and the Adams-Birch FEM monitor. Since it was not detected at the Globeville station, the scaling had no effect on increasing the $PM_{2.5}$ concentrations for that day.

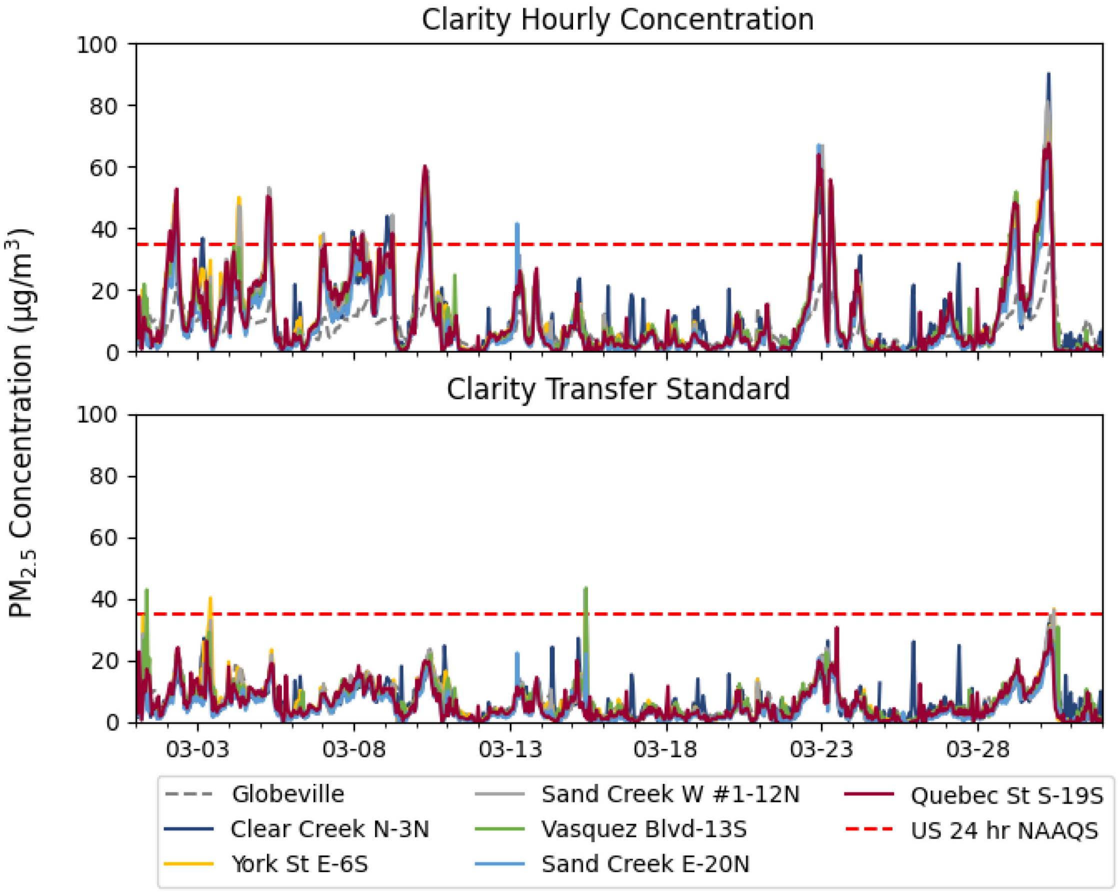

Figure 5. Time series of Clarity Node-S $PM_{2.5}$ measurements before (top) and after (bottom) scaling to the Globeville FEM monitor

Note: The scaled Globeville Clarity Node-S measurements are not shown because they were the same as the Globeville FEM monitor measurements after scaling.

3.3 Accuracy Assessment for Compliance with Colorado SB260 Monitoring

The accuracy assessment focused on $PM_{2.5}$ for three reasons, which are listed below.

1. Under CRS 43-1-128 (the codified statue of SB260), $PM_{2.5}$ monitoring is required to be in place during construction.

2. The mass concentration of $PM_{2.5}$ (reported in $\mu g/m^3$) is typically similar between individual stations within the same air mass, which made it reasonable to compare the nearby CDPHE monitors to the NSIM sensors along the I-270 corridor. This is not the case for the mass concentration of PM_{10}, which is often dominated by localized emissions that disperse or settle before reaching another nearby monitor. Therefore, the methods used in this study are not appropriate for assessing overall accuracy of PM_{10} measurements.

3. The EPA has developed guidance for the performance of NSIM sensors to which the current measurements can be compared. The EPA recommendations are based on 24-hour averages for $PM_{2.5}$; however, the results are also given for hourly measurements. There are aspects of SB260-related monitoring that require sub-daily measurements, so it is also useful to characterize sub-daily performance.

The accuracy of the $PM_{2.5}$ measurements for the 2B Tech AQSync, TSI Environmental DustTrak, Lunar Outpost Canary-S, and QuantAQ MODULAIR™-PM was assessed by comparing to the Clarity transfer standard. This is not one of the EPA-recommended methods for evaluating $PM_{2.5}$ sensor performance; however, it is recommended by the EPA to correct measurements. Several tests were used to evaluate the performance. Since the evaluation was based on the Clarity transfer standard measurements, only sensors collocated with a Clarity Node-S were included.

In this study, two TSI Environmental DustTrak sensors, two 2B Tech AQSync sensors, one QuantAQ MODULAIR™-PM sensor, and two Lunar Outpost Canary-S sensors were evaluated. The evaluation period was November 1, 2022, through July 31, 2023, which is when the Clarity Node-S was collocated at the Globeville site, and the TSI Environmental DustTrak sensors and 2B Tech AQSync sensors were installed. The QuantAQ MODULAIR™-PM was installed for only a trial period of one month, so the results from the comparison of the QuantAQ MODULAIR™-PM with the transfer standard are inherently more uncertain due to less data.

The overall accuracy of the measurements was determined by several methods. The first method used a linear regression to compare the hourly Clarity transfer standard measurements to the hourly measurements of the NSIM sensor. Figures 6 and 7 show the scatter plots of each comparison. Table 5 provides summaries of linear regression parameters (slope, y-intercept, R^2) for daily average comparisons. The daily average linear regression parameters were compared to the EPA recommendations for $PM_{2.5}$ performance metrics. The comparisons to the Clarity transfer standard measurements that are given here should be considered alongside comparisons of the NSIM sensors with FEM/FRM monitors that are presented in Section 4.2.

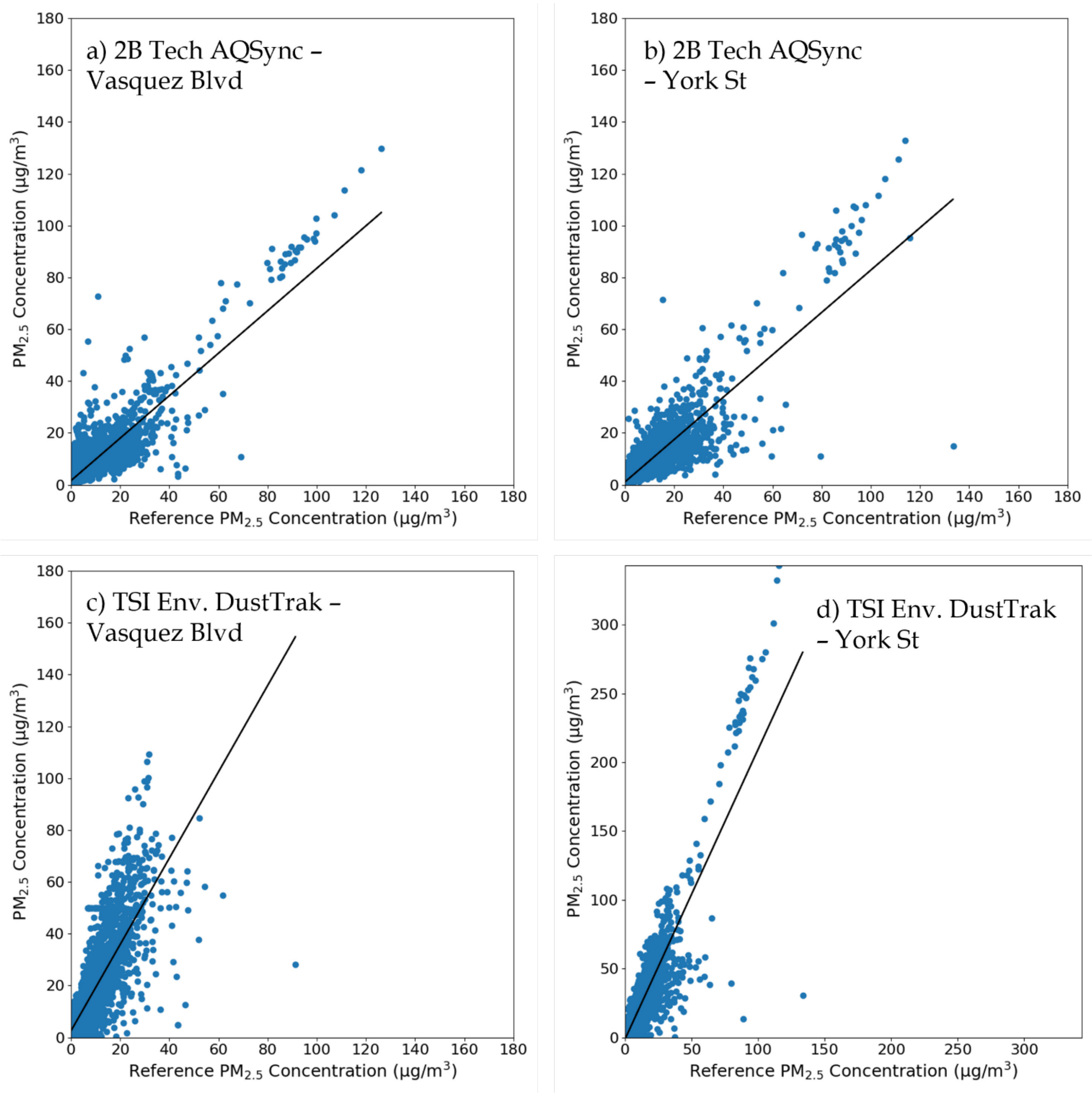

Figure 6. Scatterplots comparing the I-270 NSIM sensor data to the collocated, scaled Clarity Node-S sensor data from November 1, 2022 through July 31, 2023.

Note: Data are compared for hourly averages. a) 2B Tech AQSync – Vasquez Blvd 13S, b) 2B Tech AQSync – York St 6S, c) TSI Environmental DustTrak – Vasquez Blvd 13S, and d) TSI Environmental DustTrak – York St 6S.

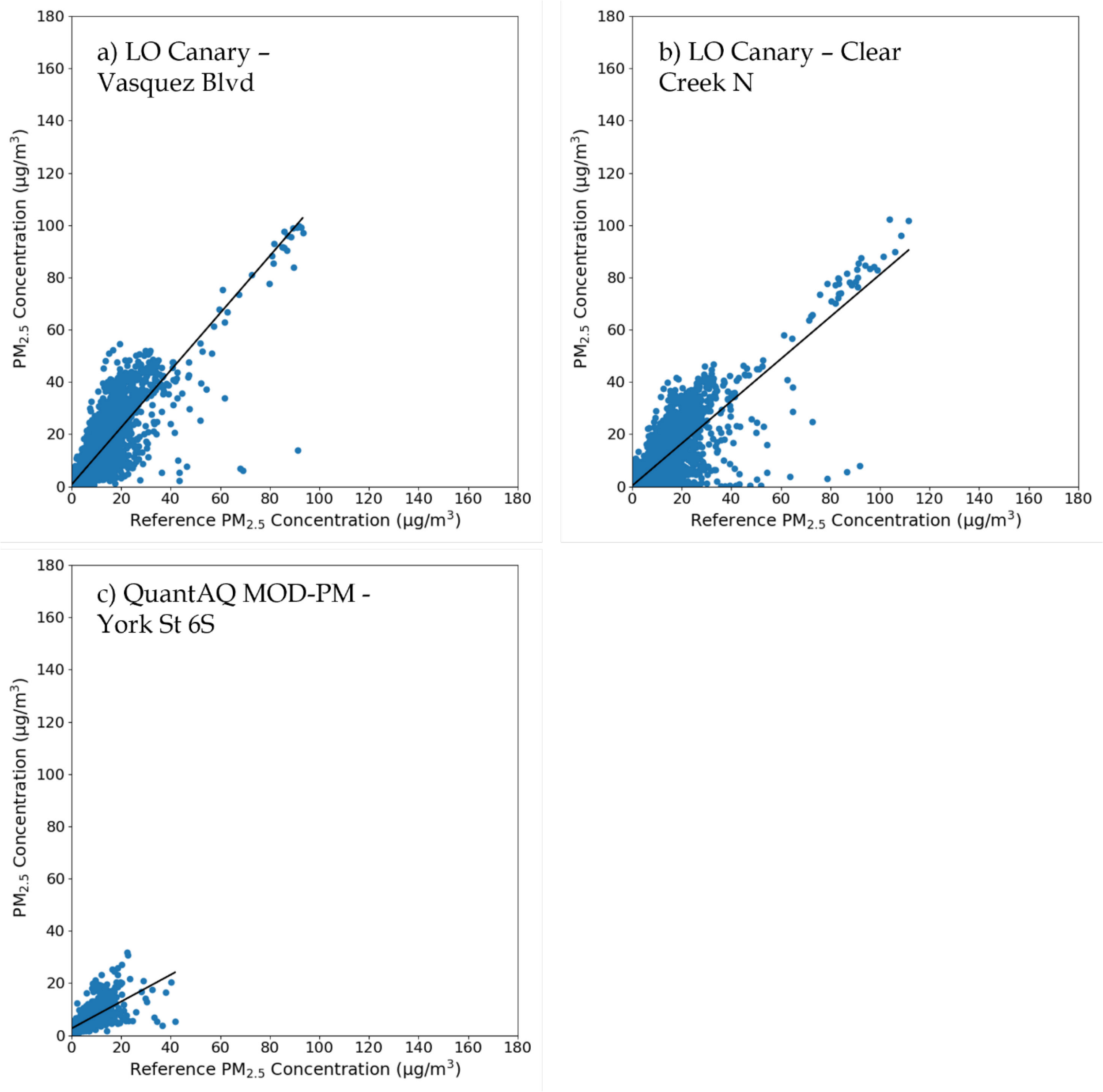

Figure 7. Scatterplots comparing the I-270 NSIM sensor data to the collocated, transfer standard Clarity Node-S sensor data (November 1, 2022 through July 31, 2023.

Note: Data are compared for hourly averages. a) Lunar Outpost Canary-S – Vasquez Blvd 13S, b) Lunar Outpost Canary-S – Clear Creek N 3N, c) QuantAQ MODULAIR™-PM – York St 6S.

Table 5. Accuracy assessment of I-270 NSIM sensors compared with FEM or transfer standard Clarity Node-S sensor measurements for daily averages.

Note: Values not within the EPA recommendations have 'NS' after them.

Device – Location	Slope	y-intercept	R^2
Clarity Node-S – Globeville	1.76 NS	-2.22	0.88
2B Tech AQSync – Vasquez Blvd 13S	0.88	1.09	0.81
2B Tech AQSync – York St 6S	0.98	-0.17	0.86
TSI Environmental DustTrak – Vasquez Blvd 13S	1.88 NS	0.50	0.80
TSI Environmental DustTrak – York St 6S	2.35 NS	-3.65	0.91
Lunar Outpost Canary-S – Vasquez Blvd 13S	1.09	0.60	0.85
Lunar Outpost Canary-S – Clear Creek N 3N	0.96	-0.97	0.87
QuantAQ MODULAIR™-PM – York St 6S	0.72	1.20	0.72

Of all the NSIM sensors tested, only the uncorrected Clarity Node-S and the TSI Environmental DustTrak sensors did not meet the EPA's recommended performance metrics.

The uncorrected Clarity Node-S overestimated the $PM_{2.5}$ concentration by 73 percent on average. There was a strong correlation between the Clarity Node-S and Globeville FEM monitor measurements ($R^2 = 0.78$). This means that, once calibrated, the Clarity Node-S $PM_{2.5}$ measurements are suitable for use as a transfer standard.

Compared to the Clarity transfer standard, the QuantAQ MODULAIR™-PM and 2B Tech AQSync sensors underestimated the $PM_{2.5}$ concentration. The former underestimated the $PM_{2.5}$ concentration by 49 percent; however, this collocation was only a month long, and the $PM_{2.5}$ concentrations observed were all below 50 $\mu g/m^3$. The QuantAQ MODULAIR™-PM uncertainty for $PM_{2.5}$ measurements during this short collocation was within the range recommended by the United Kingdom Environment Agency's Monitoring Certification Scheme (MCERTS). A longer collocation over a broader range of conditions may change the average relationship between the Clarity Node-S transfer standard and the QuantAQ MODULAIR™-PM.

The 2B Tech AQSync sensors underestimated the $PM_{2.5}$ concentration by 18 percent, which is within the recommended range of uncertainty for the MCERTS program. Of the two 2B Tech AQSync sensors, the unit at the Vasquez site had the slope closest to 1, the y-intercept closest to 0, and the R^2 closest to 1. This is also the site that had the broadest range of observed $PM_{2.5}$ concentrations. At the Vasquez site, there were numerous values above 50 $\mu g/m^3$, and these higher-value measurements showed the best agreement with the Clarity Node-S transfer standard measurements.

The Clear Creek Lunar Outpost Canary-S sensor underestimated the $PM_{2.5}$ concentration by 19 percent, and the Vasquez Lunar Outpost Canary-S sensor overestimated the $PM_{2.5}$ concentration by 9 percent. Both percentages are within the recommended range for the MCERTS program.

Similar to the 2B Tech AQSync, the Lunar Outpost Canary-S appears to be more accurate at higher $PM_{2.5}$ concentrations.

On the other hand, the TSI Environmental DustTrak sensor overestimated the $PM_{2.5}$ concentration by 66 to 111 percent. These two comparisons should be interpreted with caution because the Vasquez TSI Environmental DustTrak was not functioning during the period in which the highest $PM_{2.5}$ concentrations were observed. When this period is omitted from the linear regression between the TSI Environmental DustTrak at York St, the slope is 1.67, the y-intercept is 2.04, and the R^2 is 0.69. This suggests that both TSI Environmental DustTrak sensors performed similarly, and the difference in linear regression statistics shown in Table 5 is due to the use of different datasets in the comparisons.

There are several key limitations to drawing conclusions of agreement based on only the linear regression statistics. One limitation is that linear regressions can be particularly sensitive to outliers, as well as values at the higher end of either the independent or dependent variable range. For example, there is a time frame from May 19 to 20, 2023, when all operational NSIM sensors in the study observed a regional air pollution event that caused the highest $PM_{2.5}$ concentration measurements observed during the research project. The relationship between these data points has greater influence over the linear regression output compared with values on the lower end of the measurement range. As previously mentioned, they had the effect of changing the slope on the TSI Environmental DustTrak fit from 1.67 to 2.11.

Another limitation is that the linear regression represents an average fit, yet individual measurements can be much different than this average. Therefore, the linear regression provides information about the overall relationship between the two measurements, but individual time periods may differ greatly. The R^2 is one indication of how representative linear regression is of the overall relationship.

The regional air pollution event from May 19 to 20, 2023, resulted in higher-than-normal $PM_{2.5}$ concentrations observed throughout the Denver metropolitan area. The source of the air pollution was smoke from wildfires in Canada, which was determined based on smoke plume maps available from remote sensing. Historic smoke maps are available from the National Oceanic and Atmospheric Administration’s Hazard Mapping System Fire and Smoke Product site (https://www.ospo.noaa.gov/Products/land/hms.html). As the global climate changes, the frequency, duration, and extent of wildfires are all expected to increase.

These data are included in this report because they are representative of conditions that may be encountered episodically during transportation air quality monitoring. However, it may also be the case that the response of sensors is different for $PM_{2.5}$ from transportation sources compared with $PM_{2.5}$ wildfire sources. In Figures 6 and 7, it appears that for the 2B Tech AQSync and Lunar Outpost Canary-S sensors, the $PM_{2.5}$ measurements for the wildfire smoke agree relatively better with the Clarity Node-S transfer standard compared to the rest of the dataset. This was not the case for the TSI Environmental DustTrak that was operational during the event (York St) and measured $PM_{2.5}$ concentrations over twice as high.

3.4 Event Detection Results

Accuracy of event detection was evaluated in two ways. The first was the fraction of events, identified by the Clarity transfer standard, the sensors were capable of detecting. The second was the extent to which the sensors overpredicted events compared with the Clarity transfer standard.

3.4.1 Accurate Detection of $PM_{2.5}$ Events

To determine the accuracy of the NSIM sensors around the 35.4 $\mu g/m^3$ "event" threshold, first, the hours for which the transfer standard Clarity Node-S concentration exceeded 35.4 $\mu g/m^3$ were identified ('Scaled Clarity Hours ≥ 35.4 $\mu g/m^3$'). Then, the concentration of the NSIM sensor for those hours was compared to the scaled Clarity concentration in three ways:

1) If the NSIM sensor concentration was greater than 35.4 $\mu g/m^3$, it was treated as an accurate detection ("Hours Detected")

2) The average absolute difference between the scaled Clarity Node-S and the NSIM sensor was reported for the hours when the Clarity Node-S concentration was greater than or equal to 35.4 $\mu g/m^3$ ("Average absolute difference")

3) For any hours the I-270 sensor did not measure above 35.4 $\mu g/m^3$ and the Clarity Node-S unit did, the average underprediction difference was reported ("Average underpredicted difference")

These comparisons are summarized for each I-270 NSIM sensor in Table 6.

Table 6. Accurate prediction of hourly $PM_{2.5}$ events

Device – Location	Scaled Clarity Node-S hours ≥ 35.4 µg/m³	Hours detected	% Internal alerts detected	Average underprediction (µg/m³)
Clarity Node-S – Globeville	66	61	92%	7
2B Tech AQSync – Vasquez Blvd 13S	75	50	67%	23
2B Tech AQSync – York St 6S	93	52	56%	27
TSI Environmental DustTrak – Vasquez Blvd 13S	27	20	74%	33
TSI Environmental DustTrak – York St 6S	95	84	88%	31
Lunar Outpost Canary-S – Clear Creek N 3N	96	54	56%	31
Lunar Outpost Canary-S – Vasquez 13S	69	52	75%	31
QuantAQ MODULAIR™-PM – York St 6S	4	0	0%	28

Given the results from the comparison of hourly concentrations (see Section 3.2), it is not surprising that the 2B Tech AQSync, Lunar Outpost Canary-S, and QuantAQ MODULAIR™-PM sensors all underpredicted the number of internal alert events. Likewise, since the TSI Environmental DustTrak sensor overall measured higher $PM_{2.5}$ compared with the Clarity Node-S, it is not surprising that it captured most of the internal alerts (74 to 88 percent). It is interesting that despite its systematically higher $PM_{2.5}$ concentration measurements, the TSI Environmental DustTrak still missed 12 to 26 percent of the internal alert events. Across all sensors, the average underprediction was between 23 and 33 µg/m³.

3.4.2 Overprediction of $PM_{2.5}$ Events

Another concern related to CRS 43-1-128 monitoring is how often the 35.4 µg/m³ threshold would be incorrectly exceeded by the NSIM sensors. Table 7 shows the results from this study. The second column contains the total number of hours for which the corresponding NSIM sensor was above 35.4 µg/m³ but the Clarity Node-S transfer standard was not. The third column presents the value in the "Hours" column as a percentage of the total hours for which measurements were available for both the NSIM sensor and the Clarity Node-S transfer standard. The last column presents the average difference between the NSIM sensor–measured and the Clarity Node-S transfer standard–measured $PM_{2.5}$ concentration for all overpredicted hours.

Table 7. Overpredicted hourly $PM_{2.5}$ concentration resulting in a false internal alert

Device – Location	Hours ≥ 35.4 µg/m³	Percentage of total hours (%)	Average overprediction (µg/m³)
Clarity Node-S – Globeville	442	7.2%	30
2B Tech AQSync – Vasquez Blvd 13S	8	0.2%	31
2B Tech AQSync – York St 6S	0	0%	--
TSI Environmental DustTrak – Vasquez Blvd 13S	287	6.7%	31
TSI Environmental DustTrak – York St 6S	36	0.6%	27
Lunar Outpost Canary-S – Clear Creek N 3N	53	0.9%	12
Lunar Outpost Canary-S – Vasquez Blvd 13S	109	1.8%	17
QuantAQ MODULAIR™-PM – York St 6S	0	0%	--

The TSI Environmental DustTrak at Vasquez incorrectly measured a $PM_{2.5}$ hourly concentration above 35.4 µg/m³ for 6.7 percent of the total operating hours. The Clarity Node-S at Globeville did so for 7.2 percent of the total operating hours. These are the two highest percentages of incorrectly identified hours of any NSIM sensor. The third highest was 1.8 percent, which was from the Lunar Outpost Canary-S at Vasquez. All other NSIM sensors incorrectly measured a $PM_{2.5}$ hourly concentration above 35.4 µg/m³ for less than 1 percent of operating hours.

4.0 Discussion

4.1 Clarity Node-S Continuous Subset

Sensor accuracy is usually assessed by collocating the sensor with an FEM/FRM monitor. In this study, we used the EPA continuous subset method to adjust the measurements of a network of Clarity Node-S sensors. Each sensor in this network was then used as a transfer standard to which other nearby sensor measurements could be compared. This method used $PM_{2.5}$ measurements from a Clarity Node-S sensor collocated with an FEM monitor to develop an hourly scaling factor that was then applied to other regionally deployed Clarity Node-S sensors for each hour. This method was reasonably successful. However, several limitations of the method were identified.

The concept of using a collocated NSIM sensor to develop a scaling factor for similar NSIM sensors is based on several assumptions. One is that for a given ambient $PM_{2.5}$ concentration, the two NSIM sensors will measure and report the same $PM_{2.5}$ concentration. In a collocation study conducted by the South Coast Air Quality Management District (SCAQMD), the hourly concentrations from three Clarity Node-S sensors (Unit N5L7, Unit Y3GK, and Unit 5KGG) were compared to a Met One BAM (FEM designated). The slope, intercept, and R^2 values for each unit in comparison to the BAM (summarized in Table 8) were all similar. Note that in the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) report, the FEM measurements are on the y-axis. The slope and intercept were transformed to represent the FEM measurements on the x-axis, as is the convention used for this study. These field evaluations demonstrate that the Clarity Node-S sensors measure similar $PM_{2.5}$ mass concentrations between sensors for a given set of local conditions and that the measurements can be adjusted to better match the collocated FEM. This finding demonstrates that the Clarity Node-S sensors have "very low" measurement variations between sensors for $PM_{2.5}$ mass concentration, making them a good choice for the continuous subset adjustment method.

Table 8. Field evaluation summary for the Clarity Node-S

Field test type	Clarity Node-S unit	Slope	Intercept	R^2
AQ-SPEC	N5L7	1.38	-3.97	0.7327
AQ-SPEC	Y3GK	1.25	-2.48	0.7579
AQ-SPEC	5KGG	1.39	-4.10	0.7384

An additional assumption is that the bulk of the $PM_{2.5}$ mass at the study sites is the same composition and similar concentration as at the Globeville site. This assumption is based on several studies that show mass concentrations of $PM_{2.5}$ in an urban setting are usually dominated by aged PM that is uniform in composition throughout the urban area (Zhang et al., 2007; Jimenez et al., 2009). This assumption appears to have been valid for much of the study period because there is a good correlation between the Clarity Node-S transfer standards and the NSIM sensors.

However, the limitations of this assumption may lead to systematic errors in concentration comparisons due to compositional differences at the separate locations. Systematic error could result from difference in PM composition between locations. For example, most of the NSIM sensors measured, on average, lower concentrations compared with the Clarity Node-S transfer standard. This could mean these NSIM sensors all underpredict ambient PM, or it could mean the transfer standards overpredict ambient PM. The latter could be the case if the ambient PM at the study sites has a large mass fraction of PM that differs in composition (i.e., size, density, sphericity, and ratio of light absorption to light scattering) compared with local sources at the Globeville site.

Another assumption of the transfer standard method is that measurements by the Clarity Node-S along the study area are representative of ambient conditions. This would mean that even if the Clarity Node-S measures high or low relative to measurements made by an FEM monitor, it is measuring ambient $PM_{2.5}$. Unfortunately, this may not always be the case. In a study by Rueda et al. (2023), the authors found that certain types of NSIM sensors do not reliably measure particles from 1.0 µm to 2.5 µm. The Clarity Node-S and Lunar Outpost Canary-S sensors use the Plantower photodetector, which is known to have this issue. This may be why the Clarity Node-S and Lunar Outpost Canary-S sensors both failed to detect the PM event on March 31, 2023. This sensor deficiency can be corrected using the transfer standard method in cases where the proportion of the mass concentration attributed to PM from 1.0 µm to 2.5 µm is the same between the site that is collocated with an FEM monitor and the remote site. However, the Clarity Node-S transfer standard method may provide limited information for instances where the local $PM_{2.5}$ concentration has a different proportion of PM from 1.0 µm to 2.5 µm compared with the FEM collocated site.

Finally, this method of developing a standard may not be appropriate for other criteria pollutants. For example, PM_{10} often has local sources that disperse quickly downwind; therefore, the type and concentration of PM_{10} can be dominated by local influences. There is less known about the agreement between measurements made for NO_2/NO, O_3, and CO by collocated NSIM sensors. Therefore, the suitability (or lack thereof) for using this method for these pollutants is unknown.

4.2 Sensor Accuracy

Many companies claim their NSIM sensor provides “near-FRM” measurement capabilities; however, this is not a quantifiable statement, as there is no “near-FRM” designation or associated DQOs. Ideally, NSIM sensors are collocated with an FEM monitor in the general geographic location of the project for at least one month before deployment to evaluate the calibration models. This is not always possible due to time constraints or if the project site does not have a nearby FEM monitor. Therefore, an NSIM sensor with a default calibration model that measures PM with acceptable accuracy is desirable.

One challenge with accurately measuring PM is accounting for the influence of RH and water absorption onto particles. There are three different methods used by the sensors in this study to account for the influence of water on PM measurements.

- The TSI Environmental DustTrak and 2B Tech AQSync use an inlet heater (the same method used by FEM monitors) to ensure water on particles is not measured as part of the mass concentration. The heater turns on above a threshold RH to induce water evaporation. This method is effective and proven to eliminate this interference.

- The Lunar Outpost Canary-S and Clarity Node-S have RH measurements on the sensors that are incorporated into a calibration model to calculate mass concentration from sensor signal.

- The QuantAQ MODULAIR™-PM uses theoretical calculations based on Köhler theory (Köhler, 1936) to adjust the calculation of mass concentration from sensor signal based on the RH.

Of the three methods used by NSIM sensors to correct for RH interference, the heated inlet is the most effective. Depending on the application, the calibration model and the theoretical calculations are also effective. For untested geographic locations, the theoretical calculations for the QuantAQ MODULAIR™-PM are likely to provide better adjustment for RH influences compared with the calibration model. The calibration model is likely to provide better adjustment for RH and other influences in areas with a dense network of FEM monitors with which the NSIM sensor can be collocated periodically. It is important to note that in the absence of a heated inlet, there are limits of RH corrections. In other CDOT monitoring locations, the PM measurements from the QuantAQ MODULAIR™-PM are sometimes invalid due to rapid water condensation onto the PM. This causes the particles to grow rapidly, resulting in an overestimation of PM_{10} mass concentration. Water condensation onto PM is the same process by which clouds and fog are formed, and it is likely to occur under the following conditions: low temperatures, high RH, and stagnant wind.

SCAQMD has been very active in conducting collocation studies of many NSIM sensors with its FEM/FRM monitors at its station in Diamond Bar, California, as part of its AQ-SPEC program. The AQ-SPEC evaluations report on the accuracy of the sensors with respect to the FEM/FRM monitors for sub-hourly, one-hour, and daily averaging periods. They also report the percentage of data recovered during the test period and intra-unit variability. Several of the sensors used in this study have been evaluated by the AQ-SPEC program: Clarity Node-S, Lunar Outpost Canary-S, Met One AQ Mass Profiler (same $PM_{2.5}$ and PM_{10} hardware as the 2B Tech AQSync), and the QuantAQ MODULAIR™-PM. The following subsections provide summaries of the AQ-SPEC results, comparisons to the results of this study, and general discussion of each sensor's accuracy.

Although this study uses the EPA performance metrics as the basis for accuracy assessment, it is important to note that several non-EPA governmental organizations have also established criteria for measurements that can be used for nonregulatory purposes. These include the European Union, the Environment Agency of the United Kingdom, and SCAQMD.

The European Parliament has published guidance under Directive 2008/50/EC on the ambient air quality and cleaner air for Europe. This guidance describes "indicative measurements" as meeting DQOs that are less strict than those required for "fixed measurements." The indicative DQOs for $PM_{2.5}$ and PM_{10} are an uncertainty within 50 percent and a minimum coverage time of 14 percent, with a minimum of one measurement per week at random, evenly distributed over the year or eight weeks evenly distributed over the year. The fixed measurements are required to meet more stringent DQOs and can be used for regulatory purposes (similar to the EPA FEM/FRM designation). The fixed DQOs for $PM_{2.5}$ and PM_{10} are an uncertainty within 25 percent and no definition of minimum time coverage. The minimum data capture for measurements of pollutants from both fixed and indicative methods is 90 percent.

4.2.1 Lunar Outpost Canary-S

In a 2019 AQ-SPEC study on the Lunar Outpost Canary-S with an FEM monitor, SCAQMD reported an average slope of 0.76 across three sensors for a comparison of one-hour averages (SCAQMD 2019). The average y-offset for the Lunar Outpost Canary-S sensors was 0.9 $\mu g/m^3$, and the R^2 values were all around 0.72. The comparison to the transfer standard Clarity Node-S one-hour measurements presented in this study observed slopes that were slightly closer to 1.0 (0.81 to 1.09), slightly lower y-offsets (0.31 to 0.71 $\mu g/m^3$), and similar R^2 values (0.69 to 0.75). As seen in Figure 2, the Lunar Outpost Canary-S sensors also generally capture the same diurnal trends as the nearby FEM monitors (Globeville and Adams-Birch), except for the dust event on March 31, 2023.

The 24-hour regression analyses from both this study and the 2019 SCAQMD study show that the Lunar Outpost Canary-S meets the EPA target criteria for performance.

4.2.2 2B Tech AQSync

In this study, the 2B Tech AQSync underestimated the hourly average $PM_{2.5}$ concentration compared with the Clarity Node-S transfer standard by about 50 percent. However, when compared directly to the nearby FEM monitors (Figure 2), the 2B Tech AQSync measurements visually appear to match quite well and certainly follow the general diurnal $PM_{2.5}$ trends. Unlike the Clarity Node-S and Lunar Outpost Canary-S sensors, the 2B Tech AQSync measurements during the dust event on March 31, 2023, agree well with the FEM monitor measurements.

The AQ-SPEC program also conducted a collocated study of the Met One sensor, the AQ Mass Profiler, which is the sensor that measures PM in the 2B Tech AQSync. The AQ Mass Profiler was evaluated as part of the Met One ES-405 (SCAQMD, 2021). For the one-hour comparison of the Met One ES-405 to the FEM monitor, the average slope for the three sensors was 0.80, the average y-offset was 4.0 µg/m^3, and the R^2 values were around 0.81. Overall, the Met One ES-405 agreement with the FEM monitor is similar to the 2B Technologies AQSync agreement with the Clarity transfer standard.

The regression analyses for the daily averages comparing both the Met One ES-405/FEM and 2B Technologies AQSync/Clarity transfer standard indicates the PM$_{2.5}$ sensor meets the EPA criteria for performance.

4.2.3 QuantAQ MODULAIR™-PM

The AQ-SPEC program evaluated the QuantAQ MODULAIR™-PM and determined it has excellent correlation (R^2 = 0.8441 to 0.8955) with the collocated FEM monitors for hourly PM$_{2.5}$ measurements (SCAQMD, 2022). Overall, the QuantAQ MODULAIR™-PM was found to overestimate the hourly PM$_{2.5}$ concentration by about 30 to 40 percent. In contrast, this study found that, compared with the transfer standard, the QuantAQ MODULAIR™-PM underestimated the hourly average PM$_{2.5}$ concentration. However, the current QuantAQ MODULAIR™-PM collocation lasted for only one month. Additionally, the effect of correcting the Clarity Node-S (which overestimated the PM$_{2.5}$ concentration by 70 percent on average) compared with the Globeville FEM monitor may be influencing the perceived accuracy of the QuantAQ MODULAIR™-PM.

In both the SCAQMD evaluation and this study, the regression analyses for the daily averages of PM$_{2.5}$ measured by the QuantAQ MODULAIR™-PM indicate the sensor meets the EPA criteria for performance.

4.2.4 TSI Environmental DustTrak

The TSI Environmental DustTrak has not been evaluated by the AQ-SPEC program; therefore, the only evaluation considered here is this study. The slope of the linear regression, which was 1.88 and 2.35 for the two TSI Environmental DustTrak sensors, indicates this sensor overestimates the PM$_{2.5}$ concentration by 88 to 135 percent. The R^2 values (0.80 and 0.91) suggest there is good correlation between the TSI Environmental DustTrak and the Clarity transfer standard, so it may be possible to provide a correction factor to obtain better agreement.

The regression analysis for the daily averages of PM$_{2.5}$ measured by the TSI Environmental DustTrak showed that this sensor does not meet the EPA criteria for performance.

4.3 NSIM Sensor Suitability for CRS 43-1-128 Compliance of PM Measurements

Two NSIM sensors evaluated in this study meet the requirements for measuring PM$_{2.5}$ and PM$_{10}$ as part of during-construction monitoring of planned RS/TC projects: the 2B Tech AQSync and the QuantAQ MODULAIR™-PM. Both sensors measure $PM_{2.5}$ and PM_{10}, and $PM_{2.5}$ measurements are reasonably accurate (within 35 percent for daily averages). These findings are based on this study, as well as data from the AQ-SPEC program. As mentioned previously, although the Lunar Outpost Canary-S and Clarity Node-S sensors report PM_{10}, it is well-documented that these measurements are not suitable for any use. In addition to accuracy, which was discussed in Section 4.2, there are several criteria to consider when choosing an NSIM sensor for during-construction monitoring:

- Cost
- Power requirements
- Accompanying meteorological information
- Ease of transferring validated data to public-facing dashboards in near-real time

In terms of cost, the QuantAQ MODULAIR™-PM is the best option for measuring $PM_{2.5}$ and PM_{10}. The 2B Tech AQSync is around 30 times the cost of the QuantAQ MODULAIR™-PM.

The QuantAQ MODULAIR™-PM is also the best option in terms of power consumption; it runs on a small, low-cost ($495) solar panel and battery system. The 2B Tech AQSync has a commercially available option for solar power, as well. However, due to the larger power consumption, the cost of the solar power system is around $25,000. Despite the higher cost, the 2B Tech AQSync solar panel system would be suitable for highway construction project monitoring. The solar panel and battery backup are mounted to a trailer to which the AQSync can also be mounted. This solar power system was developed by 2B Tech in collaboration with Wanco, which specializes in traffic safety products.

For ambient air quality monitoring, accompanying measurements of wind speed and direction, temperature, and RH are recommended. As part of the standard package, the 2B Tech AQSync comes with a high-quality meteorological sensor attachment. It is not yet possible to attach meteorological equipment directly to the QuantAQ MODULAIR™-PM; however, the manufacturer has indicated it is testing this capability and intends to have it commercially available in the future. Since high-quality meteorological stations are readily available and can be configured alongside the QuantAQ MODULAIR™-PM, this is not an impediment to measuring the desired meteorological parameters. The cost of a separate meteorological system will vary.

The final consideration is the ease of transferring validated data to public-facing dashboards. The QuantAQ MODULAIR™-PM and 2B Tech AQSync both have well-documented APIs that are easy to use. However, none of them can flag invalid data on the manufacturer platform. Therefore, if transferred directly from the manufacturer platform to CDOT, data may contain invalid records that are then shared with the public. To solve this problem for the I-270 research project, the data were first transferred to eagle.io, a third-party platform for aggregating and reviewing data. The data from eagle.io were then transferred to the CDOT database using a well-documented API. The eagle.io platform can also configure customizable data alerts based on individual measurements. Since not all data flagging occurs in real time, the CDOT queries pull in modified data so that once data are invalidated, they are no longer displayed on the public-facing dashboard.

5.0 Conclusions and Recommendations

There are dozens of NSIM sensors commercially available, each with a unique set of capabilities and measurement accuracy. (See Table A1 in Appendix A for a summary of some of the more popular NSIM sensors.) Many NSIM sensor technologies for measuring PM use light-scattering and optical methods, which can have variable accuracy based on the type of sensor, the local meteorological conditions (e.g., temperature, relative humidity, wind speed), and the composition and size of the PM.

This report provides several examples of criteria that should be considered when evaluating the suitability of an NSIM sensor for a specific application. This process should be followed for evaluating any NSIM sensor proposed for a particular use. The general recommendations for using and evaluating NSIM sensors—as outlined in the EPA's *Enhanced Sensor Guidebook* (Clements et al., 2022), previous studies discussed in this report, and this study—are listed below.

- Review information available from third-party sources about the capability and accuracy of an NSIM sensor before choosing it for a specific application.
- Do not use PM_{10} data from any NSIM sensor that uses a light-scattering device (e.g., Plantower or Sensirion) for PM measurements. These are only suitable for $PM_{2.5}$.
- Evaluate the accuracy of the data compared with an FEM monitor using the EPA criteria for performance for $PM_{2.5}$.
- It is important to take into account data accessibility and NSIM sensor operation considerations in relation to user capabilities.
- The ability to flag invalid data to exclude from the dataset is an important feature that is not available through NSIM sensor platforms.

5.1 NSIM Sensor Accuracy

Periods of collocation and subsequent adjustments to calibration models or factors are recommended to improve the accuracy of measurements. There are general guidelines for collocating NSIM sensors with FEM monitors.

- Data collected at hourly averages should have a minimum of two weeks of collocation, and one month is the preferred duration.
- If possible, conduct collocations of NSIM sensors during each season, as meteorological conditions will affect measurements.

For additional information about evaluating NSIM sensors by collocation with FEM monitors, see *How to Evaluate Low-Cost Sensors by Collocation with Federal Reference Method Monitors* (Environmental Protection Agency, 2023).

This study evaluated an alternative approach to periodic collocation. Specifically, the continuous subset method to adjust data from the Clarity Node-S sensors was used to develop “transfer standards.” This method was successful in improving the agreement with the measurements made by the Clarity Node-S sensors deployed along I-270 with the measurements from the Globeville FEM monitor.

However, the question remains as to how accurate the transfer standards are for representing the local ambient PM. In one instance, another FEM monitor and several of the other NSIM sensors measured much higher $PM_{2.5}$ concentrations compared with observations at the Globeville site. For this case, the transfer standard did not agree well with local conditions. Therefore, this method has limitations for detecting local emissions. It is recommended to also conduct periodic collocations with each sensor and an FEM monitor. Additionally, this method is not likely appropriate for measuring pollutants other than $PM_{2.5}$.

5.2 Suitability Evaluation

The example application investigated in this study is the suitability of NSIM sensors for collecting PM measurements during the construction of planned RS/TC projects. During-construction monitoring requires measurements of $PM_{2.5}$ and PM_{10}, an action plan to address “events” when concentrations are above specific thresholds, and the transfer of data to a public-facing dashboard. Of the NSIM sensors evaluated, the QuantAQ MODULAIR™-PM is the most suitable for during-construction monitoring because of the balance of accuracy with cost, power requirements, and portability. The QuantAQ MODULAIR™-PM meets the EPA criteria for $PM_{2.5}$ measurements.

5.3 Additional Measurements

Many of the near-road tailpipe emissions are small particles that do not have much mass. Therefore, it may be useful for transportation projects to look at the number concentration of particles in either the $PM_{2.5}$ size range or a smaller size range, such as PM with an aerodynamic diameter less than 1.0 µm. Additionally, many of the small particles emitted are from incomplete combustion. These are generically referred to as soot and may be quantified with an aethalometer. Recently, some portable aethalometers have become commercially available and are marketed as measuring “black carbon.” These alternative measurements may be useful for CDOT in future studies.

6.0 References

Clements, A., Duvall, R., Greene, D., & Dye, T. (2022). The enhanced air sensor guidebook. U.S. Environmental Protection Agency, Washington, DC. https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=545843&Lab=CEMM

Duvall, R., Clements, A., Hagler, G., Kamal, A., Kilaru, V., Goodman, L., Frederick, S., Johnson Barkjohn, K.K., VonWald, I., Greene, D., & Dye, T. (2021). Performance testing protocols, metrics, and target values for Fine particulate matter air Sensors: Use in ambient, outdoor, fixed site, non-regulatory supplemental and informational monitoring applications. U.S. EPA Office of Research and Development, Washington, DC, EPA/600/R-20/280. https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=544837&Lab=CEMM

Environmental Protection Agency. (2023). Instruction guide and macro analysis tool: Evaluating air sensors by collocation with federal reference monitors. https://www.epa.gov/air-research/instruction-guide-and-macro-analysis-tool-evaluating-air-sensors-collocation-federal. Last updated December 14, 2023.

Font, A., et al. (2014). Degradation in urban air quality from construction activity and increased traffic arising from a road widening scheme. *Science of The Total Environment.* 497-498: 123-124. http://dx.doi.org/10.1016/j.scitotenv.2014.07.060

Harleman, M., et al. (2023). Changes in traffic congestion and air pollution due to major roadway infrastructure improvements in Texas. *Science of The Total Environment.* 898: 165463. https://doi.org/10.1016/j.scitotenv.2023.165463

Isakov, V., et al. (2014). Air quality modeling in support of the near-road exposures and effects of urban air pollutants study (NEXUS). *Int. J. Environ. Res. Public Health*. 11, 8777-8793. https://doi.org/10.3390/ijerph110908777

Jimenez, J.L., et al. (2009). Evolution of organic aerosols in the atmosphere. *Science*. 326(5959). 1525-1529.

Kinsey, J. S., Linna, K. J., Squier, W.C., Muleski, G.E., & Cowherd, C. (2004). Characterization of the fugitive particulate emissions from construction mud/dirt carryout. *Journal of the Air & Waste Management Association*, 54(11), 1394–1404. https://doi.org/10.1080/10473289.2004.10471007

Kittelson, D. B. (1998). Engines and nanoparticles: a review. *Journal of Aerosol Science*. 29(5-6), 575-588. https://doi.org/10.1016/S0021-8502(97)10037-4

Köhler, H. (1936). The nucleus in and the growth of hygroscopic droplets. *T. Faraday. Soc.*, 43, 1152–1161, 1936.

Li, C., & Managi, S. (2021). Contribution of on-road transportation to PM2.5. *Sci Rep.* 11, 21320. https://doi.org/10.1038/s41598-021-00862-x

Muleski, G. E., Cowherd, C., & Kinsey, J. S. (2005). Particulate emissions from construction activities. *Journal of the Air & Waste Management Association*, 55(6), 772–783. https://doi.org/10.1080/10473289.2005.10464669

Perkinson, D.G. (1998). Air quality impacts of highway construction and scheduling. *Texas Department of Transportation Report*. Report 1745-S

Rueda, E.M., Carter, E., L'Orange, C., Quinn, C., & Volckens, J. (2023). Size-resolved field performance of low-cost sensors for particulate matter air pollution. *Environmental Science & Technology Letters*. 10 (3), 247-253. https://doi.org/10.1021/acs.estlett.3c00030

Samuels, G., & Freemark, Y. (2022). The polluted life near the highway: A review of national scholarship and a Louisville case Study. *Metropolitan Housing and Communities Policy Center*.

SCAQMD. (2019). Field evaluation: Lunar Outpost Canary-S. Available at: http://www.aqmd.gov/aq-spec/sensordetail/lunar-outpost-canary-s

SCAQMD. (2021). Field evaluation: MetOne ES-405 Particulate Profiler. Available at: http://www.aqmd.gov/aq-spec/sensordetail/metone---es-405

SCAQMD. (2022). Field evaluation: QuantAQ – MODULAIR™-PM. Available at: http://www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/quantaq-MODULAIR™-pm---field-evaluation.pdf?sfvrsn=15

Tanfeng, C., Russell, R. L., Durbin, T. D., Cocker, D. R., Burnette, A., Calavita, J., Maldonado, H., & Johnson, K. C. (2018). Characterization of the emissions impacts of hybrid excavators with a portable emissions measurement system (PEMS)-based methodology. *Science of The Total Environment*. 635: 112-119, https://doi.org/10.1016/j.scitotenv.2018.04.011.

TSI Incorporated. (2012). DustTrak II aerosol monitor and DustTrak DRX aerosol monitor impactor penetration efficiency curves: Application notes EXPMN-003 Rev B. Available at: https://tsi.com/products/aerosol-and-dust-monitors/aerosol-and-dust-monitors/dusttrak%e2%84%a2-ii-aerosol-monitor-8530/

Zhang, Q., et al. (2007). Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes. *Geophys. Res. Lett.* 34(13).

Zhu, Y., Hinds, W.C, Kim, S., Shen, S., & Sioutas, C. (2002). Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmos Environ*. 36(27), 4323-4335, https://doi.org/10.1016/S1352-2310(02)00354-0.

Appendix A – NSIM Sensor Examples

Some of the more widely used NSIM sensors, the pollutants they measure, and their cost are summarized in Table A1. Note that the 2B Tech AQSync has FEM-grade modules for NO_2 and O_3.

Table A1. NSIM sensor examples

Manufacturer and model	Pollutants measured	Cost	Notes
2B Tech AQSync	$PM_{2.5}$, PM_{10}, $NO_2^{\&}$, $O_3^{\&}$, CO, CO_2	$60,000	Solar power not included in price
Aeroqual AQY R	NO_2, O_3	$5,000	Data transmission and solar power not included in price
Aeroqual Dust Sentry	$PM_{2.5}$, PM_{10}	$15,840/year or $13,079 purchase + $960/year	Includes solar power and data transmission
Clarity Node-S	$PM_{2.5}$, NO_2	$1,400/year	Includes solar power and data transmission
Lunar Outpost Canary-S	$PM_{2.5}$, TVOC	$1,300 + $100/year	Includes solar power and data transmission
Met One E-Sampler	$PM_{2.5}$, PM_{10}	$5,500	Data transmission and solar power not included in price
PurpleAir Flex Air Quality Monitor	$PM_{2.5}$	$309 (+$10 for SD card)	Wi-Fi connection only
Sensit SPOD	TVOC	$5,470 + $350/year	Includes solar power and data transmission
TSI Environmental DustTrak	$PM_{2.5}$, PM_{10}	$18,135 + $1,350/year	Solar power not included
Vaisala AQT410	NO_2, CO, O_3, SO_2	$3,700	Data transmission and solar power not included in price
QuantAQ MODULAIR™-PM	$PM_{2.5}$, PM_{10}	$1,995 + $300/year	Includes solar power and data transmission