Airborne Diesel Particulate Monitoring in Portland, Oregon

This report reviews Multnomah and Washington County particulate monitor data, equipment, and data analysis methods. Low-cost particulate monitors using a Plantower sensor first became commercially available in 2016. Before then, Portland-area particulate monitor data was available for only ten locations chosen by Oregon Department of Environmental Quality (DEQ). Residents and DEQ have recently purchased and deployed over 65 low-cost Plantower-based particulate monitors in Portland including PurpleAir, Pocketlab Air, SensOR, and hand-built versions. A Pocketlab Air has GPS location capability; when mounted on a bicycle it can record particulate for 3,600 locations per hour.

This report reviews twelve low- and high-cost particulate monitors, each with fundamental limitations that are eliminated when a diversity of monitors are used in concert. Only expensive particulate monitors can determine the ratios of diesel particulate and woodsmoke in a sample. Low-cost particulate monitors can act as an extension of the expensive device, using this ratio to determine airborne diesel particulate concentrations for a vastly larger area with up to 95% accuracy when using a correction method.

Diesel particulate is the most dangerous air pollutant to human health in urban areas. Both diesel particulate and woodsmoke are comprised of airborne carbon particles 0.1 micron or smaller in diameter coated in heavy metals and toxic chemicals. Diesel particulate easily enters the bloodstream via the lungs and accumulates in our organs, including our brains, due to an almost unique ability to cross the blood-brain barrier. The State of California reported that diesel particulate is currently "responsible for about 70% of California's estimated known cancer risk attributable to toxic air contaminants."

DEQ reported in 2015 that diesel exhaust causes lung and bladder cancer, certain heart attacks and other blood clotting diseases, coronary artery disease, malignant childhood brain tumors, decreased cognitive functioning, increased incidence of Lou Gehrig's disease (ALS), acute bronchitis, and asthma. A study by Bishop et al. found that diesel particulate causes dementia and Alzheimer's disease. Immediate symptoms include eye and throat irritation, coughing and phlegm, swollen airway, bronchial irritation, nausea, headache, lightheadedness, and fatigue.

According to the EPA 2014 National Air Toxics Assessment (NATA) released in August 2018, Multnomah County ranked among the worst 1% of counties nationwide for both airborne diesel particulate and woodsmoke exposure. Multnomah was 43rd worst nationwide of 3,224 counties and County equivalents for airborne diesel particulate and 27th worst nationwide for woodsmoke exposure out of 3,170 counties and county equivalents. NATA modeled Multnomah county's average airborne diesel particulate concentration as 0.78 μg/m3 (micrograms per cubic meter); the worst census tract in the county averaged 1.25 μg/m3.

Particulate monitor equipment

A particulate monitor must be able to either measure two types of airborne carbon (speciation) or have a resolution as low as 0.1 microns to specifically detect diesel particulate. Handheld monitors can be bicycle mounted to scan large areas.

Key aspects of particulate monitors described in this paper:

Model	cost	resolution	speciation	handheld
Aethalometer	$29,000	NA	Yes	No
BAM 1020	$20,600	NA	No	No
DEQ SensOR	$3,000	0.3 –10	No	No
MiniWRAS	$38,700	0.01 to 35	No	Yes
Nephelometer M903	$7,000	NA	No	No
OC-EC Field Analyzer	$20,000	NA	Yes	No
Partisol Plus 2025	$21,000	NA	No	No
PM2.5 speciation	$456/sample	NA	Yes	No
PocketLab Air	$300	0.3 –10	No	Yes
PurpleAir PA-II	$250	0.3 –10	No	No
Sensorbot	$50	0.3 –10	No	No
Teledyne API T640	$21,500	0.18 – 20	No	No

Filter-based particulate monitor

DEQ currently uses **Thermo Scientific Partisol Plus 2025 Sequential Ambient Particulate Sampler** monitors to measure PM2.5 in three locations in the Portland area using the Federal Reference Method (FRM). The FRM uses a filter which is weighed before and after sampling. Prior to weighing, the filter is conditioned in a temperature- and relative humidity-controlled room to eliminate any moisture differences. Weight is divided by the flow volume of the sampling period to get the concentration. DEQ 's FRM monitors are 22 years old, are starting to fail, are expensive to operate, and only provide data every third day.

Scattered light optical sensor particulate monitors

Over the next 1-2 years or more DEQ is replacing these 20-year-old Partisol Plus 2025 Portland-area FRM particulate monitors with continuous, real-time Federal Equivalent Method (FEM) equipment. DEQ has a contract to start purchasing the EPA FEM approved **Teledyne API T640** PM monitors at a cost of $21,500 each. This device uses an LED lamp and optical sensor to reports airborne concentrations of 64 particle sizes from 0.18 – 20 microns in diameter.

DEQ has been using the **Radiance Research M903 nephelometer** at seven Portland-area sites. A nephelometer measures light scattering using a flashlamp and a light detector. Radiance was purchased by Met One instruments around 2015. DEQ is replacing their 20-year-old nephelometers with DEQ SensOrs. **DEQ SensOrs** are particulate monitors designed and built by DEQ that include a Plantower sensor, heated inlet to reduce interference from humidity, regulates air sample flow, an automated quality control check software, and cellular communication to post real-time data. SensOr monitors are currently located at four Portland-area locations and will be deployed soon at eight new Portland-area sites. All DEQ real-time particulate monitor data is online at: https://oraqi.deq.state.or.us/home/map

DEQ FRM PM2.5 Portland-area annual averages

DEQ monitor site	2018 daily	2018 average	2019 daily	2019 average
5824 SE Lafayette St, Portland	17.4	6.8	20	6.5
Hare Field, Hillsboro	22.2	7.2	23.6	6.7
Tualatin near I-5	19.5	7.1	20.5	6.8

FRM averages reported in µg/m3. The daily standard is among the highest readings, calculated by DEQ by using the 98th percentile of the daily, 24 hour averages. This confirms whether a short term standard was systematically exceeded.

In 2016, the $250 **PurpleAir PA-II** became commercially available, using a Plantower sensor. Each single particle that passes through a Plantower sensor interrupts a laser, which scattered light and generates a pulse on a photodetector. PurpleAir report the airborne particulate concentration total for 0.3 –10 micron diameter particles every 120 seconds in µg/m3. Portland Clean Air is working to compile and graph Portland-area PurpleAir data is online at: purpleair.com/map?opt=1/mAQI/a10/cC0#11/45.5288/-122.6821

We are concerned about PurpleAir licensing which states that all data and even the purchased devices themselves are the property of PurpleAir. We emailed them and they responded: "We are currently working on a good 'terms and conditions' for the data but just expect curious use of the data and give us credit as the creators of the data."

EPA scientists developed a correction equation for PurpleAir monitors after finding that they are biased. Under higher humidity PurpleAir monitors consistently overestimate fine particle concentrations compared with the regulatory-grade monitors that are operated in the same location. PurpleAir now includes the EPA correction option in its software. All Plantower sensor-based monitors require such a correction. A Study by California South Coast Air Quality Air Management District compared PurpleAir to best available high-cost FRM/FEM reference instruments. A result of "1" would be a "near perfect correlation":

PM1 .96 to .98
PM 2.5 .93 to .97
PM10 .66 to .70

Plantower-based monitors had some minor inconsistencies to consider. The low-cost sensors were less accurate at low PM concentrations and with varying temperature and humidity. This is addressed by using correction methods available from the EPA and others. This also suggests low-cost monitors should not be deployed individually; redundancy allows for outlier detection.

Starting in 2017, Portland resident Chris Eykamp independently purchased Plantower sensors and bulk electronics, wrote software, and created Wi-Fi **Sensorbot** monitors for $50 each. Chris deployed these stationary devices with community support to 19 Portland locations and recently released up to three years of data per device. This project currently requires volunteer(s) for data processing.

In April 2019, the $300 **PocketLab Air** became available using a Plantower sensor with GPS location capability. The PocketLab takes a reading once a second, reading 3,600 locations per hour when bicycle mounted. Portland Clean Air purchased 14 PocketLab Air and Quad Lock bicycle mounts in 2019 so we can collect enough data in three hours to GIS map PM1 for every location on every street for square miles of Portland at a time. Because diesel particulate peaks between 10 am and 1 pm, all data collected during these times, in the same day, is an apples-to-apples comparison. Such a map can portray airborne diesel particulate concentrations caused by truck trips per day on busy routes. Pattern changes occur due to wind speed and direction, inversion, and other factors.

Only high-cost monitors can specifically measure airborne diesel particulate and woodsmoke; they detect the unique color or size of these particles. This can determine the ratio of diesel particulate and woodsmoke in PM1. Low-cost equipment can collect PM1 and then use this ratio to determine diesel particulate concentration for large areas.

One device that detects particles as small as diesel particulate and woodsmoke is a condensation particle counter. Particles that are too small to scatter enough light to be detected by conventional optics are grown to a larger size by condensation. The **TSI Model 3007** is a $10 K hand-held condensation particle counter, a portable lightweight device that records 0.01 to >1.0 micron particle counts by drawing an aerosol sample continuously through a heated saturator, in which alcohol is vaporized and diffused into the sample stream and passed into a cooled condenser. Particles grow quickly into larger alcohol droplets and pass through an optical detector where they are counted. However, the TSI 3007 only counts particles so its readings cannot be compared to the readings of other monitors included in this report.

Organic carbon (OC) /elemental carbon (EC) particulate monitors

The **Magee Aethalometer,** a $29 K instrument, provides a real-time readout of the concentration of airborne carbon by measuring transmitted light intensities through filter media on which the aerosol spot is collected. This includes "black" or "elemental" carbon (EC) aerosol particles in an air stream, caused primarily by diesel exhaust, and "brown" or "organic" carbon (OC), caused primarily by woodsmoke.

Portland Clean Air obtained DEQ Aethalometer readings following by information request and calculated averages for sites in Portland, Gresham, Hillsboro, and Tualatin. The Tualatin site was the closest to a major truck route, 100 feet from I-5. On 10/26/18 ODOT counted 871 trucks in 24 hours approximately one thousand feet north from that site. Daytime peaks at the Tualatin site were as high as 4.17 μg/m3. Outdoor airborne diesel particulate may be double that concentration along I-5 in Inner NE Portland where ODOT has counted as many as 1,593 trucks per 24 hours.

DEQ Aethalometer readings

Site	Date Start	Date end	EC Carbon	OC Carbon
Cully	5/18	12/19	0.50	0.79
Humboldt School	1/17	12/19	0.54	0.97
Gresham	12/16	12/17	0.52	0.73
Tualatin I-5	1/17	12/19	0.96	1.35

Averages reported in μg/m3 calculated by Portland Clean Air

The EPA PM2.5 Speciate Database reported that "Portland/Seattle woodstove combustion" is 80% OC, 17% EC; various other compounds make up the rest; diesel particulate is 53% OC, 42% EC; various compounds make up the rest. A 2009 study by James Noll reported that diesel particulate carbon speciation percentages vary depending on the type of engine and year of manufacture. Portland Clean Air used these values to write a formula to calculate airborne woodsmoke and diesel particulate concentrations from OC/EC data:
OC/TC = X
(X - .442) x 2.61 = woodsmoke proportion AKA WP
(WP x TC = woodsmoke TC) / .97 = woodsmoke PM
(TC - Woodsmoke TC = Diesel TC) / .95 = diesel PM

Site	DEQ diesel	DEQ wood smoke	EPA Tract Diesel PM
Cully	0.753	0.591	0.704
Humboldt School	0.758	0.814	0.944
Gresham	0.747	0.477	0.609
Tualatin I-5	1.527	0.885	0.678

DEQ Aethalometer conversions in µg/m3 by Portland Clean Air compared to diesel and woodsmoke census tract modeled averages from 2014 EPA NATA released 2018

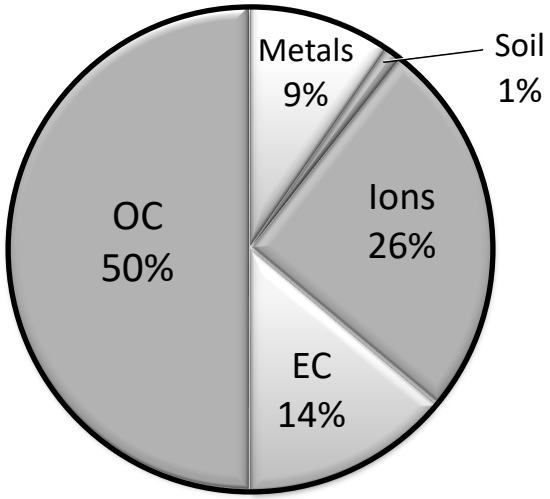
Studies on OC/EC monitoring including reviews by the Center for Disease Control's National Institute for Occupational Safety and Health often cite Bob Cary at Sunset Laboratory in Tualatin, Oregon, who builds an approximately $20K **OC-EC Field Analyzer** that speciate airborne carbon more accurately than an Aethalometer. An air sample is heated rapidly in a helium environment to release OC, then cooled and heated more slowly with oxygen in order to release the carbon in EC. An optical laser measures the results. This device requires a standard power outlet, compressed gases, and a highly skilled operator.

Airborne carbon monitors such as the Aethalometer and OC/EC Field Analyzer are primarily lab equipment. However, they could be operated from a car powered by an inverter plugged into the cigarette lighter. Truly portable equipment is battery powered and can be easily carried or bike mounted. Easy to use, portable, highly accurate scientific equipment for particulate monitoring that can detect particles as small as .01 micron is available. The only drawback is that these portable devices cannot differentiate woodsmoke from diesel particulate**.** This can instead be addressed through comparative statistics or including Aethalometer data.

Because this report is focused on diesel particulate we used only wildfire-excluded data and no data from 2020, which excluded three new DEQ Portland-area monitor sites. The 2020 West Coast wildfires were the worst in California and Oregon history. On 9/12 and 9/13/2020 the Air Quality Index website listed Portland as having the worst air pollution in the world at that time. On those days DEQ's SE Portland Lafayette FRM monitor PM2.5 reading peaked extremely high at 536 µg/m3 and the DEQ Aethalometer at Humboldt School, Portland peaked at a staggering 24.32 µg/m3 for black carbon and 108.93 for brown carbon.

PM2.5 speciation involves collecting samples on a filter for 24 hours every third day. A lab gradually heats the filters, releasing different portions of the carbon at different times; the burn-off is measured with gas chromatography and mass spectroscopy. Organic carbon volatilizes off the filter first, then elemental carbon. Here are the averaged results of PM2.5 speciation of 643 fall and winter samples collected by DEQ from 2015 to 2020 at their SE 5824 Lafayette, Portland monitoring station:

Portland DEQ PM2.5 speciation results



From SE 5824 SE Lafayette, fall & winter 2015-2020

Beta attenuation particulate monitor

Met One Instruments' Model BAM 1020 was the first instrument to obtain U.S. EPA Federal Equivalent Method (FEM) designation for continuous PM2.5 monitoring. At the beginning of each sample hour, a small beta-radiation source emits a constant source of high-energy electrons through clean filter tape. These beta rays are detected and counted by a sensitive detector and compared to tape loaded with ambient dust collected from the outside air. The Air Monitoring Program of the Bullseye Glass settlement is collecting PM2.5 data with a BAM 1020 at six locations near the Brooklyn Rail Yard in Inner SE from 10/2/19 to May 2022 at a cost of $1 M. An independent engineering firm, Weston Solutions, is conducting the monitoring. Due to the 2020 wildfires we excluded this data, available online at: https://westoncloud.net/rtairmonitoring/Download?l=SS DEQ is also considering the BAM 1020 to replace its aging FRM equipment.

Particulate monitor that combines optical and electrical particle detection

The **Model 1371 Grimm Mini Wide Range Aerosol Spectrometer (MiniWRAS)** is the only portable instrument on the market that allows simultaneous and precise real-time monitoring of both micron-sized and nanoparticles. This $38.7 K device counts particles and measures their individual sizes, on 41 evenly spaced channels from .01 to 35 microns using a spectrometer and an electrometer. This is a small enough resolution to directly measure diesel particulate leaving the vehicle tailpipe which is 0.01 microns; diesel particulate quickly aggregates to 0.1 microns. The Grimm electrometer is portable and can be bicycle mounted. Data is collected and logged on a laptop which can incorporate GPS locations. The Grimm electrometer cannot differentiate diesel particulate from woodsmoke.

A study by Samad et al. using the Grimm electrometer, an Aethalometer, and a TSI 3007 Condensate Particle Counter in urban Germany were attached to a tethered weather balloon which was winched up and down to take readings from ground level up to 470 meters. This study provided data about the ratio of black carbon, PM1, and PM2.5 using the most accurate particulate monitors. This study recorded PM2.5 was approximately 5 μg/m3, and PM1 and black carbon were each near 2 μg/m3. This is an example of a ratio needed to interpret Plantower readings. A Grimm electrometer is urgently needed in Portland so low-cost monitor readings can be translated into diesel particulate and woodsmoke concentrations.

When there was not an inversion, black carbon dropped approximately 25% every 50 feet of elevation. During an inversion, Samad et al. demonstrated that black carbon, PM1, and PM2.5 remained fairly constant up to 150 feet in elevation. That means even penthouse condos can get the same diesel particulate and woodsmoke from an open window as housing at the ground level. This may explain the black sooty buildup people wash off their penthouse windows in downtown Portland. During an inversion, they noted particulate levels dropped by half at about 300 feet.

What you can do

Portland Clean Air is requesting donors fund a Grimm Electrometer so we can compare diesel particulate and woodsmoke in indoor and outdoor air and determine the ratios of diesel particulate and woodsmoke that comprise Portland Plantower-based sensors readings.

Outreach to groups of experienced bicyclists is needed. The PocketLab Air study requires 10 riders collecting samples from 10 am to 1 pm, allowing us to comparatively map particulate in a large area of the city, which has never been done before.

We would love to connect with you if you have experience with Excel graphing or using SQL for large datasets and have time to volunteer. We are working to graph Portland data from DEQ, Sensorbot, Bullseye settlement monitoring, and PurpleAir monitors.

If you have questions, comments, or would like to volunteer or donate please contact Greg at: greg@portlandcleanair.org

Written by Greg Bourget 4/25/2021

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