Key operational processes and systems involved in hyperlocal monitoring efforts include:

a. **System procurement and installation** (e.g. instrumentation specifications, installation locations (stationary and/or mobile), power supplies, etc.)

b. **Instrument system performance check** (e.g. performing instrument checks, calibration, etc.)

c. **Instrument deployment and operations** (e.g. installation, maintenance, troubleshooting, quality assurance and calibration, etc.)

d. **Data management and processing** (e.g. logging data and metadata from multiple instruments at adequate speed, storing or streaming it in real time to a server, robust data quality assurance and quality control procedures, etc.)

Additionally, the following tasks are critical to ensure your project runs smooth overall:

- **Partnership management** (e.g. finalizing contracts, memoranda of understanding (MOUs), bailment agreements, and other legal agreements that insure cars, drivers, or pods)
- **Project logistics and coordination** (this can cover training drivers , finding backup sites for stationary monitors, repairing instruments, and arbitrating disputes)

A. SYSTEM PROCUREMENT

In most cases, you will seek a contractor who specializes in air pollution measurements to supply the sensor systems of your choice. There are many important elements to consider in choosing an appropriate contractor and selecting your monitoring systems.

In choosing a contractor(s) who will design, install, and manage your sensor system(s), consider their prior experience with mobile air pollution mapping, capacity to deliver, ability to respond promptly to problems and requests, and motivation to meet your needs. Keep in mind that designing a system goes beyond just selecting the right instruments and involves numerous design decisions — for instance, air inlet and tubing material can impact sample collection and resulting data. Relevant expertise and experience is key.

Here are a few examples of RFPs for soliciting bids from potential contractors, as well as criteria for evaluating proposals:

- Mobile monitoring for medium-cost instrument platform and service RFP
- Low-cost instrument platform on municipal fleet RFP
- Selection criteria for low-cost instrument platform on municipal fleet RFP

You will want to discuss in detail the performance of sensors or instruments, and whether you use a contractor or build a system yourself, see the Houston report for lessons learned and open-source design tips.

- Houston low-cost mobile final report

Key sensor or instrument performance indicators to consider:

Accuracy, Precision, and Bias.

These are foundational factors that determine the performance of your sensors or instruments. They determine how accurately the sensor or instrument measures the true value of pollution. Your data quality will be influenced by these performance characteristics.[8]

Detection range.

Is the sensor or instrument accurate at the pollutant ranges you expect in your city? Instruments may be less accurate beyond the bottom and top ranges of tested concentrations. If you have no baseline measurements, look for as broad an accurate detection range as possible.

Drift.

Over time, a sensor or instrument may change in its response to the same amount of pollution — the readings may start to "drift." Periodic checks and calibrations are needed to minimize the effect on your data. This is covered in more detail below.

Interference.

In the real world, instruments need to identify particles and gases from a mix of airborne substances. Consider whether an instrument becomes less accurate at detecting one particle or gas in the presence of other substances.

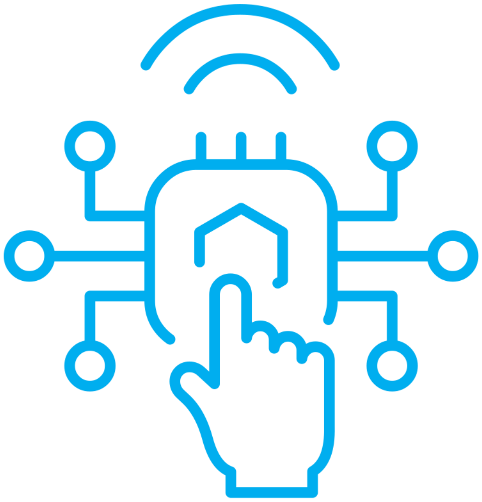
Testing environment.

Testing by independent evaluators should have taken place both in a lab and in the field. When you evaluate results from lab tests, look for tests at wide ranges of humidity and temperature.

Response time.

For mobile instruments, the response time will need to be quick — one to three seconds, depending on the driving speed. In a moving vehicle, response time will determine the resolution of your data. Note that response time tends to be slower for low-cost sensors so they may be impractical for mobile monitoring.

How do you choose your instrument? Third parties, including government organizations, have evaluated a wide range of lower-cost instruments and are doing so on an on-going basis as new sensors and sensor systems continue to proliferate in the market. See earlier list of Air Pollution Sensor and Monitor Performance Evaluation. It is recommended that you consult an air pollution monitoring expert or scientist to help evaluate and select an appropriate monitoring system if your city does not have in-house expertise.



Factors beyond performance

In addition to the factors described above, consider the operating parameters of the instrument. These factors may not be tested, because there is no independent measure of quality, and may not be described in independent testing. As a result, you should ask the instrument provider for details, and your RFP should specify all the requirements necessary to meet your monitoring needs.

Consider:

- Size and weight.
- Weather resistance.
- Ability to function in the desired vehicle or location under likely conditions.
- Additional data collected. Temperature and relative humidity may be necessary for data analysis, and wind data is very helpful for source attribution.
- Low power consumption. The system is preferably run by battery or solar power. Hardwiring or plugging into anything will significantly increase your cost and complexity of deployment, and may reduce the locations where the instruments may be deployed.
- Minimum amount of calibration and maintenance, to be conducted by non-experts if needed. Check if specialized instruments or gases are required for maintenance or calibration — these can increase project complexity.
- Data management:
  - On-board data storage for one or more days.
  - Ability to stream data through Wi-Fi, cellular, LoRaWAN, or Bluetooth without new coding on the part of the user. (Ask about the language or code in which the data output appears, and check if you have someone who can handle that kind of data.)
- Ability to remotely control the instrument or push updates. This will enable you to make improvements to your data collection abilities without physically visiting every sensor.

If you intend to measure more than one species of pollutant, you or your contractor will likely have to build your own instrument platform from a suite of sensors. Established instrument and service providers can work with you to assemble a customized package. See the different sets of instruments that EDF has used in our various projects below.

STATIONARY MONITORING NETWORK

Project	Instrument Partner	Black carbon	PM	UFP	NO	NO_2	CO_2	O_3
Oakland, CA	UC Berkeley	Custom*	-	-	-	-	-	-
London	Air Monitors Ltd	-	AQMesh					

*Note: *Custom Aerosol Black Carbon Detector built by UC Berkeley research team. Lower-cost black carbon monitors are not yet commercially available as black carbon is not yet a regulated pollutant in any country. However, research has shown that black carbon is a potent, short-lived climate pollutant, and that it can do significant harm to human health. Efforts to introduce lower-cost black carbon monitors to the market are underway.*

MOBILE MONITORING

Project	**No. of monitoring vehicles***	**Instrument Partner**	**PM2.5**	**BC**	**UFP**	**Lung Deposited Surface Area (LDSA)**	**Ozone**	**NO**	**NO2**	**CO2**	**VOC**
Oakland	2	Aclima	Proprietary information			-	-	Proprietary information		-	-
Houston	2	Sonoma Technology	Thermo-Fischer PDR-1500	Magee Scientific AE33	Aerosol Dynamics MAGIC 200p	-	Teledyne API T400	Teledyne API T200	Teledyne API T500U	LiCor LI-7000	ppbRAE 3000
Houston (Smart Fleets)	2 (municipal fleet)	TD Environmental Services	Thermo-Fischer PDR-1500	microAeth MA-200	-	-	-	-	-	-	-
London	2	Air Monitors	Thermo PDR - 1500 PM2.5 Nephelometer + FIDAS 100 PM Monitor (1, 2.5, 4, 10, and TSP)	Magee AE33 Black Carbon Monitor	-	Naneos Partector - nano PM monitor	2B Tech 211G Ozone Monitor	Serinus 40 NOx Monitor	Aerodyne CAPS Direct NO2 Monitor	LiCor Model 7200RS CO2/H2O Monitor	-

*Note: *Google Street View cars, except as noted*

Disclaimer: Any reference to any organizations, products, or services made in this guidebook do not constitute or imply the endorsement or recommendation by EDF.

Estimating costs

Cost is a key consideration when deciding on your mobile monitoring platform. We have provided a calculator for estimating the cost of procuring and running your monitoring systems.

A

CITY INPUTS
is where default assumptions about the city to be measured are stored.

B

COSTS
contains assumptions about the instruments.

C

STATIONARY
contains user inputs regarding how long it takes to obtain a stable measurement and calculates stationary project cost in total, and the cost per datapoint.

D

MOBILE FLEET
calculates how many vehicles driving their regular routes are needed based on the number of passes desired to get a stable measurement.

E

MOBILE DEDICATED
calculates the cost of mapping using a dedicated vehicle and driver on a specialized route, with repeated passes to get a stable measurement.

F

MOBILE COVERAGE
collects how many vehicles it takes to cover the city, with different numbers of passes for stable measurements.

G

MODEL OUTPUTS
sheet summarizes the results of the analysis.

When budgeting, remember that as you invest in monitors, sensors, and associated consultants to run a full monitoring campaign, you will need to dedicate staff time to project oversight. The more calibration and maintenance a consultant handles, the less your staff will have to do, although at a cost. As a result, you can specify up front with your instrument designer how much time you can allocate to instrument management.

You will also need to invest in team members or consultants to analyze and explain the results. The cost calculator above does not include these costs. It is common to fixate solely on the costs of buying and operating the hardware and underestimate the cost of maintenance, data processing, and interpreting results from the monitors. Keep in mind that while you can buy more lower-cost instruments, they may come with significant trade-offs in data quality, and may require more work during the operations phase to calibrate and maintain. Even with high-quality instruments, we find we spend $5 for data analysis and decision-making for every $1 on instruments.

Paperwork

In some cases, you may need to put in place a bailment agreement among partners to establish the terms of transfer, use, possession, and protection of properties being used in the project (e.g. monitoring instruments, vehicles, etc.). For instance, in our mobile monitoring effort in Houston, we had a bailment agreement for the monitoring equipment owned/rented by EDF, located on Google Street View cars and municipal cars.

Here are a few examples of bailment agreements:

- Project proponent and city low-cost mobile partnership and bailment agreement
- Project proponent and consultant low-cost mobile service and bailment agreement

B. INSTRUMENT SYSTEM PERFORMANCE CHECKS

Before you begin collecting data, conduct a trial of your instruments in the field to ensure that they function properly in your particular locale. Instruments can behave differently in different environmental conditions (e.g. humidity, temperature, wind, etc.). Instrument checks need to be done as the monitoring system is being built, before initial deployment, as well as routinely throughout the deployment.

CALIBRATE YOUR INSTRUMENTS AGAINST REFERENCE MONITORS

As part of preparing for deployment, it is valuable to co-locate your chosen instruments with reference instruments (where available) to verify their performance in the field. This is a critical step when you are deploying a stationary monitoring network, but also applies to checks for instruments to be used in mobile monitoring. For example, the air monitoring pods used in our Breathe London project were co-located against several regulatory monitoring sites in London. Similarly, the black carbon sensors used in our 100x100 project spent several weeks co-located with regulatory monitors in Oakland.

In some urban areas, multiple reference monitoring sites may be located in a range of environments (e.g. central city with higher concentration of pollutants vs. suburban or open space areas with lower concentrations of pollutants). When possible, select co-location sites that are representative of the environment where your instruments will be deployed.

ADDITIONAL CONSIDERATIONS FOR MOBILE MONITORING PLATFORMS

For mobile instrument platforms, run tests to assess the impact of vibrations (from driving on different road surfaces) and weather (e.g. heat, cold, rain, humidity) on instrument performance. Work with your contractor and air quality experts to conduct these tests.

Initial performance checks should also include testing to determine the time a sample travels through air tubing, as well as confirming instrument response time. This will be used to adjust data so that the concentration data is correctly assigned to the GPS location where it entered the inlet.

Ensure that a time stamp for mobile measurements is synchronized. Make sure that the time stamp assigned to your measurements is simultaneously assigned to the logged GPS coordinates. As the mobile platform travels along a road, the car's GPS records the time and place approximately every second. However, the instrument on top (or inside) of the car may record a slightly different time, thus confounding the ability to assign the measurement to the same location where it was taken. From our experience, for every measurement it is best to use a timestamp synchronized across instruments and GPS readings that's based on a GPS satellite-grade clock. Make this a requirement for your system setup and don't rely on the instrument clock.

Test the real response time to make sure that it performs at the rate in the technical specification. In addition, many instruments can be set at different response times (commonly 1, 3, 5, or 10 seconds for research grade instruments). Ensure that it is set at the appropriate rate to achieve your desired spatial resolution.

C. INSTRUMENT DEPLOYMENT, OPERATIONS, AND MAINTENANCE

STATIONARY MONITORING

Installing stationary monitors in the real world is more challenging than identifying ideal locations on a map. In addition to determining where to place your monitors to best measure the pollution or sources you want to capture, there are a wide range of site-specific factors you will want to consider, including (though not limited to):

- Access to power supply or solar power viability
- Internet or Wi-Fi connectivity
- Safety and security
- Stable support structures for attaching your monitors
- Distance from source (for example, as close to the road as possible if you are monitoring transportation emissions, or in a park or upwind of sources to get an estimate of background pollution concentration)
- Height of installation platform (placing monitors at varying heights can tell you information about street canyon effects, keeping many monitors at the same height allows an easier comparison between nodes in your network)
- Environment of the immediate surrounding area that could impact measurements (e.g. vents, grills, barriers that could obstruct air flow and host permission, whether hosts are individual residents, businesses, or public institutions)

Other guidance on micro-siting considerations you may also want to review:

- European Directive 2008/50/EC – Annex III
- U.S. Environmental Protection Agency Air Sensor Toolbox
- Greater London Authority Guide For Monitoring Air Quality in London

Gather as much information about these conditions before deploying your monitors to ensure successful installation and save time. These factors are not always within your control, so allow some flexibility in your network design.

Working with other city departments or public agencies that have networks of infrastructure suitable for monitor installation can be highly productive (e.g. a transit agency who owns and maintains street furniture, the parks department who can give broad permissions to place systems at public parks, or school districts). Getting an agreement to be able to place monitors at any school, traffic intersection, or community center, etc. is much easier than getting site-by-site agreements. Once you have that agreement, then you can overlay your ideal locations with the list of available locations.

Consider working with local groups that can help identify and reach out to many hosts, such as neighborhood groups, community-based organizations, a local chamber of commerce, or church groups. Recruiting "hosts" for your sensors or instruments and obtaining their permission can be time intensive, so consider that when creating your deployment timeline. Providing a formal host agreement or certificate of insurance can help alleviate concernsaround potential liability.

Here is an example of a host agreement form:

- Stationary sensor network host agreement form

Most stationary air quality monitors do not require daily operations, however, monitors may malfunction and need repair on occasions. Make sure this is included in the cost of your service agreement if you are employing a third-party contractor.

MOBILE MONITORING

For mobile monitoring, keep in mind that routine daily instrument operations (e.g. turning the instrument on and off, conducting instrument checks, charging batteries, etc.) may be done by drivers, with proper training. Provide simple and clear instructions as the starting point for training all your drivers.

To keep instructions streamlined, ask your contractor(s) to preset software on the instrument or to use equipment that does not require frequent cleaning or replacement. We also highly recommend that you request user-friendly SOPs (e.g., start-up and shut-down procedures/checklists, calibration procedures and frequencies, troubleshooting and maintenance, etc.) for each instrument as part of the contract. The manufacturers of certain instruments used in the Houston municipal pilot modified installed software (known as "firmware") to make the operations easier — consider asking manufacturers if this is possible for your deployment.

More complex sensor systems (e.g. medium- to higher-cost, multi-pollutant systems) usually require on-the-ground technical support who can carry out daily and periodic calibrations and checks of the monitoring systems, and provide on-going oversight of the instruments' performance.

ROUTE MANAGEMENT

If you are deploying monitoring vehicles that drive specific, pre-set routes, it is important to track your progress against the sampling plan that you laid out at the start of the project on a daily and weekly basis, and make appropriate adjustments. Simple GPS tracking apps (e.g. GPS Tracks) can be used by drivers to view the drive areas scheduled for each day. These apps also provide drivers with real-time feedback on their mapping progress relative to daily driving goals. Such systems can help drivers be more effective at reaching targeted coverage. Importantly GPS tracking systems allow you to evaluate the drive coverage at the end of each day and adjust the next day's drive plan accordingly. Some types of fleets (e.g. waste management or delivery) may have more advanced GPS tracking systems already built in.

INSTRUMENT MANAGEMENT

In our experience, it is useful to have real-time diagnostic tools that can be viewed both in the monitoring vehicles and remotely. This gives you the ability to quickly identify any issues that could affect data collection and require troubleshooting. Typically, these instrument diagnostic tools can be supplied by sensor systems providers. Some providers may be able to customize tools for your specific performance management needs.

CALIBRATION AND MAINTENANCE PROCEDURES

For both stationary and mobile monitoring, you will need to perform appropriate calibration and maintenance procedures for each instrument. Follow best practices as outlined by the instrument manufacturer in the instrument manual. Different monitoring systems require differing degrees and frequencies of calibration and maintenance, some of which involve dispatching experts with specialized equipment. If your contractor has agreed to design, install, and manage your instrument system(s), request a detailed plan for conducting and documenting calibration and maintenance as part of the contract. In our monitoring projects, we found that a local, on-the-ground field service technician saved hours and headaches by detecting and resolving instrument problems as quickly as possible.

Here are a few examples of a standard operating procedure (SOP) for a mobile monitoring platform:

- Low-cost mobile instrument O&M SOP
- Breathe London mobile monitoring instrument O&M SOP

Breathe London "Gold" Pod Calibration Procedure

The Breathe London stationary monitoring network uses small sensor-based air quality monitors that are lower cost (AQMesh). These devices are not intended to provide equivalent accuracy to reference monitoring methods, but rather to provide denser coverage at a much lower cost than existing monitoring systems. To ensure that high-quality data are obtained, these monitors are co-located with reference monitors prior to initial deployment.

In addition to this conventional practice, we conducted "gold" pod co-locations for 6 months after the initial deployment. "Gold" pods are standard AQMesh monitors which have been co-located at one or more reference monitoring locations, providing traceable evidence of the gold pod's performance. After the pod has been characterized, it serves as a "transfer standard" or "gold standard" and can be moved adjacent to a "candidate" pod located in the network for a period of approximately 7-14 days.

After this period, analysis is performed to determine the extent to which the candidate measurements agree with the gold pod. High level of agreement serves as a proxy for good performance and scaling factors are applied to the candidate pod to bring its measurements in line with the gold pod's. If the level of agreement is low, the candidate pod is investigated and necessary adjustments are made. The project team are also working to develop a network-based calibration method which would allow calibration for the entire network of monitors without additional co-location.

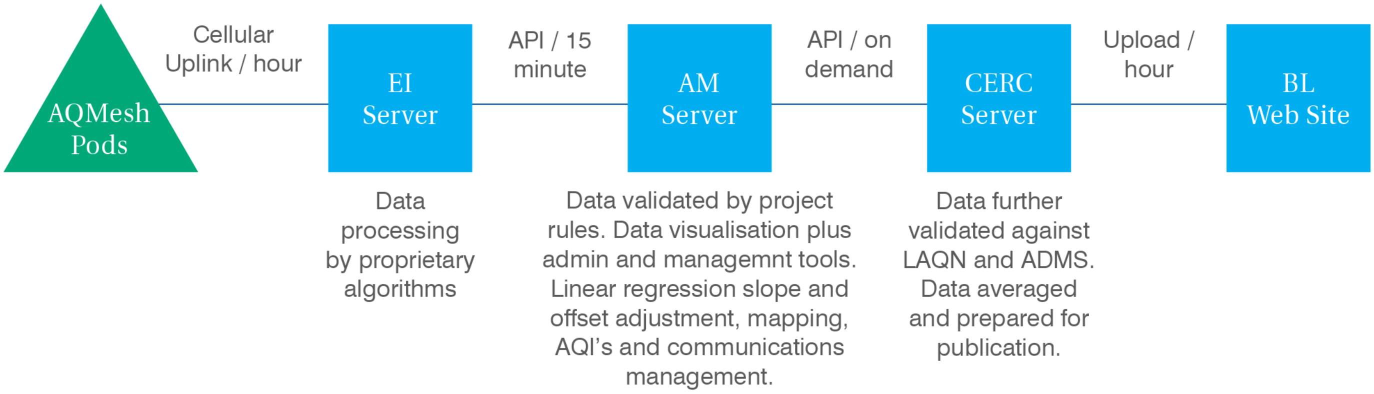
For more information on Breathe London project's data verification and quality assurance process, see the website's Methodology page.

D. DATA MANAGEMENT AND PROCESSING

DATA MANAGEMENT SYSTEM

Resources for managing the data are of critical importance. You may decide to include data management as part of the service package from your instrument provider, or by a specialist contractor.

Here is an example of a data flow and storage system from our Breathe London stationary monitor network project:



If you are creating your own data management system, consider working with a data expert to design a system that will ensure a smooth transfer of your data to storage and its final data platform.

Some detailed considerations and potential pitfalls to consider include:

- After data is transmitted from an instrument, they may go to an on-board logger before being transmitted to data storage. If you are using multiple instruments, you will need to plan for data loggers that are programmed with the necessary data channels.
- If data are not being transmitted directly to a server, ensure that your instruments have sufficient data storage.
- Particularly relevant for mobile monitoring platforms is the choice of data acquisition mechanism (streaming vs. polling). If your instrument uses a streaming protocol, make sure your data logger has a high read frequency compared to the instrument's sampling frequency, e.g. 100 Hz for measurements that stream every 1 second.

DATA TRANSPARENCY

Transparent disclosure of data in as raw a form as possible, and of data analysis methods, allows errors or biases in results to be discovered. The process of turning "raw" air pollution measurements into validated data, final maps, and everything in between requires a great deal of judgment from your team. To maximize the value of public investments and generate more insights from the resulting data, project owners should leverage the ingenuity of the scientific community by granting them access to all the data. Be sure that your partnership agreements or contracts allow you full access to all raw and processed data.

In an effort to support open access to air pollution data, EDF has developed Air Quality Data Commons (AQDC) — an open-access, open-source data platform that allows people to share and use FAIR (Findable, Accessible, Interoperable, and Reusable) data from low- and medium-cost air quality sensors while maintaining necessary data privacy and security. Air pollution data collected by EDF and partners will be made available through the AQDC platform.