EDF ENVIRONMENTAL DEFENSE FUND™
Finding the ways that work

Making the invisible visible:

A guide for mapping hyperlocal air pollution to drive clean air action

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EXECUTIVE SUMMARY

The science is clear.

Air pollution is harmful to human health, and its impacts — increased hospital visits, missed work and school days, boxes of rescue inhalers at schools — are frequent reminders that its risks are real and personal. Moreover, these risks are highest for some of the most vulnerable populations: children, the elderly, and people with already compromised respiratory systems.

Because air pollution is hard to see, it's often hard for local leaders to pinpoint sources and trends to develop effective solutions. New sensor technology is changing that dynamic, allowing us to measure and map pollution concentrations block by block and identify patterns and hotspots like never before.

Compared to conventional air pollution management, which commonly relies on a few sparsely located monitors and modeling, hyperlocal monitoring allows for a more holistic picture of air quality at a high spatial resolution (with different concentrations every 30 meters, for example) and frequency (different concentrations every minute or few minutes, rather than on an hourly or daily basis). Hyperlocal monitoring can fill a gap in places where modeled data is not available. Additionally, measuring on-the-ground pollution allows for a better understanding of the true exposure and health impacts of air pollution, which can then result in targeted solutions.

This guide provides advice on how to design, fund, implement, analyze, and leverage data from a hyperlocal air quality monitoring network, so you can develop solutions to improve health in your community.

Over the past few years, Environmental Defense Fund (EDF) has worked with scientists, technology firms, grassroots organizations, and city leaders in the United States, United Kingdom, and China to design and deploy hyperlocal air pollution monitoring systems that measure and analyze local air pollution levels. We have developed tools and gained experience that can prove useful to cities with wide ranging challenges and capacities. By sharing these tools and learning, we hope to better equip leaders to create lasting improvements to local air quality.

The world needs air quality solutions at scale. Nine out of ten people worldwide breathe polluted air from their first breath to their last. Global air pollution is now the biggest environmental risk of early death, responsible for as many as seven million premature deaths each year. That's more than AIDS, tuberculosis, and malaria combined. And recent studies have uncovered that air pollution can impact mental health, lung development, and even stock market performance.

Everyone deserves to breathe clean air, but where you live determines how likely pollution is to worsen or shorten your life. And while most conventional monitoring systems can provide a general sense of a city's air quality, they cannot account for air pollution at the neighborhood level, where people live, work, and play. Research shows that air pollution is not evenly distributed and can in fact be up to eight times worse on one end of a city block than another.

Through our work with city and community leaders, we've seen how this new kind of data can help design new solutions, build political support for action, increase compliance, and hold polluters accountable. We have also learned that robust engagement with community leaders and residents, who are directly impacted by dirty air, is critical when creating thoughtful, responsive, and impactful clean air solutions. Community engagement should be undertaken as a long-term and iterative process. Engagement through one-on-one interviews, focus groups, and citizen science campaigns will help co-produce knowledge, increase self-efficacy among community members, and ultimately build trust and ensure better results.

The world needs air quality solutions at scale.

In Oakland, California, EDF and our partners developed air pollution maps using data from a combination of stationary and mobile monitors. By combining these results with electronic health records, we could map associated health risks by neighborhood. Community leaders used them to advocate for mitigation efforts under a new air quality law seeking to cut pollution in California's most affected communities.

In addition to measuring air pollution via Google Street View cars in neighborhoods around Houston, Texas, EDF leaders worked with key city staff to test how sensor systems on municipal vehicles could alert the city to air pollution threats and determine how many sensor-equipped vehicles it would take to map air pollution across the entire city. We also worked with city officials in the wake of Hurricane Harvey to measure emission events that occurred following damage to the region's petrochemical facilities, which provided a community with information about high concentrations of benzene, a known carcinogen.

Building upon our work in the U.S., EDF along with the Mayor of London, Google, C40 Cities and others recently launched Breathe London, which combines sophisticated data analytics with state-of-the-art technology — such as mobile monitoring on Google Street View cars and over 100 stationary monitors — to collect air pollution data points at thousands of locations. This is one of the world's most comprehensive air quality monitoring networks in one of its busiest and most complex cities. These data create a baseline to help London design, tailor, and understand the impact of future clean air actions.

In China, EDF scientists and partners are working with officials to use hyperlocal insights to improve the efficacy of investigation and enforcement through microgrid networks for more accurate identification of hotspots.

Through our efforts, EDF has learned about the budget, staffing, analysis, and logistics needed to monitor, map, and, ultimately, reduce pollution at the neighborhood level. We hope these lessons support you as you consider approaches to air pollution monitoring that inform clean air solutions and foster healthier communities across your city.

How to use this guide

This guide provides advice on how to design, fund, implement, analyze, and leverage data from a hyperlocal air quality monitoring network, so you can develop solutions to improve health in your community.

01 GETTING STARTED

- Understanding your city's air quality challenges and opportunities
- Exploring tools to measure and map hyperlocal air pollution

02 NUTS & BOLTS

- Designing hyperlocal air monitoring systems
- Ready, set, go: Turning on and maintaining your network
- Making sense of the data

03 DATA TO ACTION

- Using air pollution data to develop and implement clean air solutions
- Building awareness and encouraging community engagement and support
- Measuring success and maintaining momentum

PART 01: GETTING STARTED

1. Understanding your city's air quality challenges and opportunities

This section guides you through reasons to pursue hyperlocal monitoring, and how the change you're hoping to create defines what and where you measure. This varies with the mix of pollutants in your city, stakeholders calling for action, available partners, and the need to meet specific health standards, among others.

2. Exploring tools to measure and map hyperlocal air pollution

This section surveys the data, people, technology, and funding that advance a monitoring program. It introduces the types and sources of data that may already exist and helps you take stock of where and who you might engage to build the case for your monitoring effort.

PART 02: NUTS & BOLTS

1. Designing hyperlocal air monitoring systems

After your team has defined a problem, you'll then need to design a monitoring process to solve it. This section walks you through the decisions driving the design process. You'll come to know the range of monitors and sensors and the pluses and minuses of utilizing stationary or mobile monitors for data. Tools here will clarify how different sources of pollution call for different equipment, placement, and experts. This section will also highlight staffing needs, including people to install monitors and analyze data.

2. Ready, set, go: Turning on and maintaining your network

This section draws on our work in cities around the world to share best practices for staffing, operating, and maintaining an air monitoring network. You'll also learn how to keep monitors, sensors, and the people who manage them working optimally over your desired project timeframe.

3. Making sense of the data

Here we'll survey the limits and ambiguities inherent in analyzing hyperlocal data. You'll learn how to gauge and devote the time required to make sense of the data. We also share best practices for visualizing and publicizing the data, and what it means for communities. You'll learn what questions to ask software and hardware vendors about data ownership, tracking, and quality assurance. We provide information on how to watch for errors, reconsider tactics, translate statistics for non-mathematicians, and manage across teams to chart progress toward cleaner air and healthier neighborhoods.

PART 03: DATA TO ACTION

1. Using air pollution data to develop and implement clean air solutions

Monitors and sensors serve to identify the problem; cities develop and implement solutions. In this section, we provide frameworks for joining constituents and experts to plan actions that reduce air pollution where you've found it. We'll also share how to apply your data to devise a pollution reduction plan tailored for your city, assign agencies to carry out the work, and put a set of clean air actions in motion.

2. Building awareness and encouraging community engagement and support

This section will discuss best practices for building awareness around clean air solutions. We'll discuss constructive dialogue across your staff, mission-driven NGOs, and community leaders advocating for immediate relief. We'll present case studies from our work in Oakland and Houston that underscore the importance of community engagement.

3. Measuring success and maintaining momentum

This section describes lessons we learned about keeping stakeholders aware of ongoing work, seeking and sustaining funding, and receiving feedback. These tools can also set a frame through which your team measures success — and how to parlay it into further investigation, advocacy, and science.

If your city is just beginning to engage on clean air as a priority, the material near the beginning of this guide about air pollution's impact and why it is difficult to track should prove useful. If you have already started, the resources we embed within each section can help you advance your work. You may also download this resource for future use — and note we'll be updating the guide as we and our partners glean more lessons learned along the way.

PART 01: GETTING STARTED

Understanding your city's air quality challenges and opportunities

Your community lives with an invisible problem that has wide-ranging impacts on both individuals and the economy as a whole. Parents may complain about asthma, missed school days, lower test scores, or "Ozone Action Days." Parks may sit empty because athletes' asthma attacks make games too risky. Traffic may make commuting to work or attending downtown events difficult, making your city less attractive to workers and their employers and potentially impacting economic development. You know that children, low-income communities, and communities of color suffer the most from pollution, creating concerns about equity in your city. Pinpointing and quantifying exactly where air quality is at its worst has typically been scientifically challenging and prohibitively expensive.

New, lower-cost sensor technology is allowing scientists, advocates, and government officials to better understand pollution patterns within neighborhoods and even individual city blocks. Some community-based organizations are increasingly empowered to better understand the air around them by purchasing and deploying monitors themselves. And air pollution in certain places, even in cities that might meet health-based standards, can burden or even shorten residents' lives.

Monitors and sensors on lampposts, buildings, or cars can measure specific pollutants that may be causing the most harm. Networks of lower-cost monitors can cover larger geographic areas, providing greater insights than traditional background air quality monitors, including patterns and relationships between sources and concentrations across the city. These hyperlocal air monitoring networks can help determine the sources of pollutants and target solutions to mitigate them. Using hyperlocal air pollution data and insights can also allow you to work more effectively with residents and stakeholders to reduce air pollution in overburdened communities.


United States Coast Guard, PA2 James Dillard

WHAT DO WE MEAN BY "AIR POLLUTION"?

While air pollution is not as noticeable in some parts of the developed world as it was decades ago, it is still deadly. Gases and tiny solids (or particulates) can collect in the lungs and spread to other organs, where they may cause lasting damage.[1] Particulates are particles of dust or fibers classified by diameter size of <0.1µm, 2.5µm, or 10µm, or ultrafine particulate matter (PM), $PM_{2.5}$, or PM_{10}, respectively. Black carbon (BC) is one kind of particulate matter that is both a greenhouse gas and a health risk. Gases include familiar pollutants: carbon monoxide (CO), nitrogen oxides (NO and NO_2), ozone (O_3), and sulfur dioxide (SO_2). They also include volatile organic compounds (VOCs), chemicals with high vapor pressure that can react with nitrogen dioxide and sunlight to create ozone.[2]

HOW DANGEROUS IS IT?

According to the World Health Organization, exposure to air pollution is responsible for around seven million premature deaths every year around the world. Additionally, exposure to air pollution can contribute to asthma, heart disease, respiratory diseases, and cancer, and affects child development starting from pregnancy. The public is exposed to air pollution continuously, and changing the path or progress of exposure often lies beyond any one person's control. Although air pollution varies from country to country, region to region, and neighborhood to neighborhood, exposure affects everyone. New research shows that living in areas with the most elevated levels increases heart attack risk in the elderly by 40 percent more than those living in areas with lower air pollution. This is similar to having a history of smoking.

WHERE DOES POLLUTION COME FROM?

Outdoors, what we call "ambient" pollution can come from fossil fuel-based transportation; on-site combustion such as generators, heating, and restaurant kitchens; industrial sources; waste and stubble burning; construction dust; and hazardous waste.[3] Combustion, or burning, can also send particles into the air from wildfires and from electric power plants. These sources represent diverse cross-sections of the economy. Pollutants can be primary or secondary in nature. A primary pollutant is emitted directly from a source, whereas a secondary pollutant forms when other pollutants (primary pollutants) react in the atmosphere.

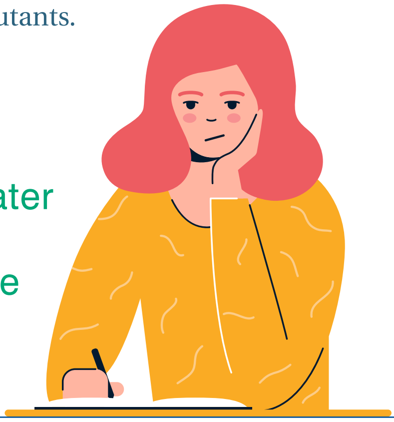
Pollutant	Characteristic	Health Effects
Nitric oxide (NO)	Primary. Associated with fuel combustion.	**Chronic:** decreased lung development, adverse birth outcomes, heart disease, asthma, premature death. **Acute:** ER visits and hospitalizations due to heart and lung disease.
Nitrogen dioxide (NO_2)	Primary and secondary. Associated with fuel combustion. Ozone precursor with more spatial variability.	**Chronic:** decreased lung development, adverse birth outcomes, heart disease, asthma, premature death. **Acute:** ER visits and hospitalizations due to heart and lung disease.
Particulate matter 2.5 (PM2.5)	Primary and secondary. Accounts for most of the health impacts of air pollution based on current research.	**Chronic:** cancer, heart disease, chronic obstructive pulmonary disease, asthma, stroke. Decreased life expectancy. Increasing evidence of impacts on brain development and function, dementia, and diabetes. **Acute:** ER visits and hospitalizations due to heart and lung
Black carbon (BC)	Primary. Marker for diesel engines, biomass burning. Directly related to source, and a climate pollutant.	**Chronic:** cancer, heart and lung disease, premature death. **Acute:** worsening of asthma, heart attacks.
Ozone (O_3)	Secondary. Less spatially variable than many primary pollutants. Variation over time due to atmospheric conditions.	**Chronic:** lung diseases like asthma, emphysema, premature death. New evidence suggests impacts on brain. **Acute:** hospitalizations and emergency room visits for asthma, other lung diseases, and stroke.
Ultra fine particles (UFP)	Primary and secondary. May be much more toxic than $PM_{2.5}$ since it penetrates into the body.	Less studied since it is highly variable and regulatory monitoring for this is limited. **Chronic:** some evidence of heart disease. **Acute:** lung inflammation and changes in markers for heart disease.
Total volatile organic compounds (VOCs)	Primary and secondary.	**Chronic:** cancer, affects brain function and development. **Acute:** lung irritation, headaches, nausea.
Carbon Dioxide (CO_2)	Primary and secondary. It is a key greenhouse gas causing climate change.	**Chronic:** Decreased food security, malaria, diarrhea, other infectious diseases, increased ozone health effects. **Acute:** Deaths, heart and lung disease due to heat waves and hurricanes. Increased allergies and asthma.

Why is understanding hyperlocal air pollution important and useful?

We use the term "hyperlocal" air pollution throughout this guide to refer to air pollution information or data at a high spatial resolution (with different concentrations every 30-60 meters, for example), and at a high temporal resolution (different concentrations every minute or few minutes, rather than on an hourly or daily basis). Different pollutants are present and travel in different ways, making a monitor in one spot often unable to detect a danger even 100 steps away. Research shows that air pollution is not evenly distributed and can in fact be up to eight times worse on one end of a city block as another.

As you learn more, you'll see cost effective ways to measure pollution in your city, even on a block-by-block scale. Some pollutants in residential areas exacerbate chronic ailments like asthma or shortness of breath for those most vulnerable, pushing otherwise healthy people into illness. Sound data on the location of particularly acute pollution can help cities more reliably develop measures to reduce exposure to harmful pollutants.

Students taking important exams on days with greater air pollution had significantly worse test scores.



Studies also show that dirty air harms the local economy, in addition to human health:

- One study showed that air pollution in central London causes the equivalent of over 650,000 sick days each year.
- Students taking important exams on days with greater air pollution had significantly worse test scores.
- Air pollution levels influenced stock trading. A study of daily data from the S&P 500 index and daily air quality data from an EPA sensor close to Wall Street found that on days with higher air pollution, stock returns were lower by almost 12 percent. These findings were replicated in analyses using data from the New York Stock Exchange and Nasdaq.
- A National Bureau of Economic Research study on the productivity of indoor workers at a pear-packing factory showed that an increase in fine particulate matter ($PM_{2.5}$) — a harmful pollutant that can easily get indoors — leads to a six percent decrease in packing speeds inside the factory.
- International businesses in cities with heavy air pollution have had to offer a form of hazard pay to woo top executives. For example, Panasonic offered their Chinese employees a "pollution premium" and Coca-Cola offered a 15 percent bonus for their employees willing to move to China. But even after relocating, many execs still choose to leave, citing pollution-related health concerns for themselves and their children.

YOU CAN'T MANAGE WHAT YOU CAN'T MEASURE

When you begin monitoring air quality, you may discover how oversights or natural disasters affect health in ways you couldn't have predicted. For example, this case study shows how EDF experts forged a partnership with Houston to reveal high levels of benzene — a highly toxic pollutant — from a damaged industrial facility in short order after Hurricane Harvey. These monitoring efforts were instrumental in drawing attention to a problem that was putting the health of Houston residents at risk in the midst of a disaster, providing critical evidence that validated residents' concerns, and highlighting the need for an investigation. The data offered a counternarrative to claims from a facility which had underreported emissions.

Residents and local officials may already suspect that pollution impacts specific areas but do not have the evidence to support their hypotheses. For example:

- Is this cement batch plant contributing to poor air quality nearby?
- Is truck traffic contributing to elevated asthma, heart attacks, or ER visits in the community?
- Are high concentrations of benzene coming from a refinery after a flood or other natural disaster?
- Do truck routes near a local elementary school cause children to miss days of school and avoid the playground?

Over the long term, it may be possible to motivate some partners and funders by highlighting interlinkages between air pollution and climate change. Many strategies to reduce air emissions can lead to a reduction in climate pollutants. Several air pollutants like black carbon are greenhouse gases (GHGs) themselves, and others are chemical precursors for greenhouse gases. For example, nitrogen oxides and VOCs emitted from power plants and other industrial sources react with sunlight to form ozone, a main contributor to radiative forcing. Rising temperatures also spur building occupants to crank air conditioners, which can inadvertently boost particulate matter levels.

As you move through this guide, you will come to understand the extent of the opportunity, as well as the complexity of the interconnected decisions you and your team will have to make. Defining your goal is the first and most powerful step to getting started.

Policies and actions that may grow from hyperlocal insights include:

- Investigation and enforcement against factories or other stationary pollution sources: prioritize enforcement resources to conduct monitoring in hotspot areas to better target the most polluting sources and most vulnerable groups in these areas.
- Emergency public health interventions: improve emergency response alerts like evacuations and shelter in place orders; optimize deployment of emergency response resources to be more responsive to varying demands in different areas or at different times, e.g. in response to wildfire smoke or an ozone action day; input into public information campaigns.
- Transportation planning (long-term): inform the design of transportation projects (such as public transit infrastructure or electric vehicle fleet investment) to provide air quality benefits where they are most needed.
- Traffic management (short-term): inform the design of traffic management measures to prioritize air quality improvements in hotspot areas. such as idling restriction rules and traffic re-routing.
- Zoning, permitting, building codes, and land use: inform land use and zoning designations to mitigate exposure of sensitive populations to high pollution areas.
- Investments and incentives for emissions-reduction projects: use hyperlocal air pollution data to prioritize investments (such as EV buses or building retrofits) in highly polluted areas.

BELOW ARE SOME FREQUENTLY ASKED QUESTIONS ABOUT REASONS TO CONDUCT AIR QUALITY CAMPAIGNS:

Why conduct hyperlocal monitoring when there's little air quality enforcement or action?

If your goal involves creating awareness of pollution, you will want to determine where hotspots exist. You may want to learn how to identify the localized presence and impact of a problem pollutant; create momentum to advocate for local, regional, or national policy or action; or build support for clean air public investments.

Why conduct hyperlocal monitoring when you already have enforcement abilities?

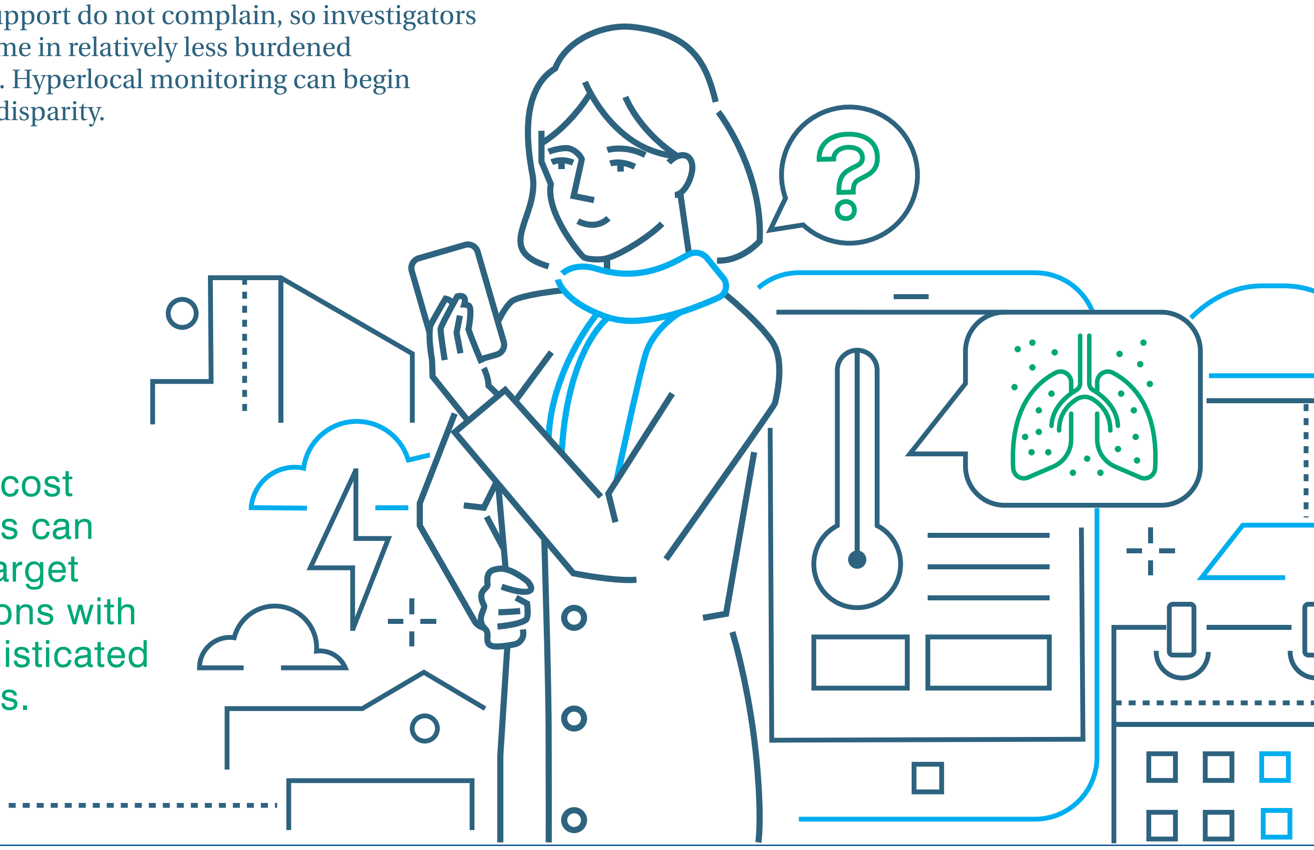
If you want to apply a specific local law or authority to bring about change in practice at a particular location, such as an industrial location or traffic intersection, you can use monitors to produce hyperlocal data that show where pollution is most prevalent. Using low-cost instruments can help you target investigations with more sophisticated instruments. Also, some leaders worry that the communities that most need enforcement support do not complain, so investigators are spending time in relatively less burdened neighborhoods. Hyperlocal monitoring can begin to address this disparity.

Why conduct hyperlocal mapping when you are making a long-term policy or infrastructure decision?

If you want to decide whether to allow a land use in a particular location, revise a building or construction code, or design transportation infrastructure, you can use monitors to understand where the health burdens from air pollution are already significant. With this information, you can better protect vulnerable populations and build for the future.

And if you want to gauge how an existing policy change has worked, use hyperlocal data to draw "before" and "after" measurements of an area. In London, our partnership measured pollution levels before and after the introduction of a new Ultra Low Emissions Zone (ULEZ). We discuss lessons learned from London throughout this guide.

Using low-cost instruments can help you target investigations with more sophisticated instruments.



Why conduct hyperlocal mapping when you are making an investment?

If you are deciding where to make investments that protect health, such as incentives to retire diesel engines, new electric vehicle bus routes, or building retrofit funds, you can use hyperlocal monitoring to target funds to neighborhoods where the policy interventions will be most effective.

As you develop your monitoring goals, you may also want to understand what your city is already considering, or doing, to tackle air pollution.

A general list of action areas to investigate in your city includes, but is not limited to:

- ☐ Congestion pricing
- ☐ Low emission zones
- ☐ Drayage truck regulations
- ☐ Cycling infrastructure
- ☐ Pedestrian zones
- ☐ Mass rapid transit
- ☐ Electric vehicle incentive programs (e.g. passenger cars, city and school buses, taxis, etc.)
- ☐ Strict car emission standards
- ☐ Demand-oriented street lighting
- ☐ Roadside vegetation buffers
- ☐ Anti-idling compliance and enforcement
- ☐ Smart traffic management
- ☐ Power plant desulfurization and denitrification
- ☐ Fugitive emission controls
- ☐ Clean construction initiatives
- ☐ Mandatory health risk assessment for expansion projects
- ☐ Energy efficiency programs
- ☐ Renewable energy rebates

Exploring tools to measure and map hyperlocal air pollution

You can procure monitors or sensors from commercial vendors. But equipment varies widely in the pollutants they measure, the complexity and quality of data quality they produce, their operational and maintenance requirements, and, of course, how much they cost. Therefore, it is important that your priorities are carefully itemized before you speak with a potential vendor. Sensor system capabilities and ease of operation can range widely, from equipment that involves relatively simple maintenance, to more complex integrated multipollutant systems that will likely require specialist support.

To decide what hyperlocal monitoring system to develop, begin with an assessment of what's already in place in your city. Laws may require that your region maintain an air monitoring network. In the U.S., the 1970 Clean Air Act requires routine monitoring of six criteria pollutants: $PM_{2.5}$, PM_{10}, carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3) and lead (Pb). Each state must have a plan to conform to health-based standards known as the National Ambient Air Quality Standards (NAAQS) for these pollutants. Most counties in the U.S. have just one — if any — air quality monitors. And while cities may have more, most areas rely on a combination of these sparsely located monitors and sophisticated modeling to determine if the air is healthy. And while they provide a snapshot of the air quality of a large area, city leaders may need data that reflects concentrations of pollutants at a community or neighborhood level that these monitors cannot provide.

Even then, you may not need to build a monitoring network from scratch. Local academic, research, or non-profit organizations may have already started monitoring air pollution. You can scan available health data, such as public inventories of national, regional, and local emissions and health conditions, to gauge your goals. Gathering well-founded data will not only help guide your goals and help you design a more thoughtful network, it will also help ground your project in a way that will prove useful in the future if you seek support for future policy recommendations.

Identifying your emissions baseline, whether air pollution, GHG emissions, or both, will be indispensable as you aim to show impact and hold people accountable at the conclusion of the data-to-action pathway. The United Nations and the World Bank have created a standard for air pollution and GHG reporting. The detailed protocol is available online as are online training courses which provide support for developing an inventory. Emission reporting will provide a method for your city to set improvement targets and measure annual trends. New York is a great example of a city that has taken the initiative to do just that: the New York City Community Air Survey is one of the largest ongoing urban air monitoring programs in the U.S. that monitors annual trends in air pollutant levels, pinpoints local sources, maps neighborhood hotspots, and tracks the enactment of regulations and policies. Try to identify in advance not only how you will track the new policy or action, but how you will quantify avoided emissions.

Even before choosing the sensor systems or their exact locations, think through ways to invite members of the public, including community advocates who understand local problems, to co-own the project. This can help you earn residents' trust and patience as you deliberate on where to put monitors, take the time to install them, and make decisions based on what they show. This case study highlights an example of a collaboration between EDF and a community-based organization in Oakland, CA that led to the use of hyperlocal data informing clean air action. In addition, politics and processes for installation of monitors vary across cities and countries. Our global partners at C40 Cities offer guidance for setting up a monitoring system that can earn legitimacy and scale up.

Local support can help build the case for funding your network design early:

- A mayor, a city council, or even a town board can compare the price of a proposed network to current spending on air pollution enforcement, which may include a van that goes out to take measurements or a set of stationary monitors to comply with national mandates. Hyperlocal monitoring can increase the efficacy of traditional enforcement.
- You can also explore any costs that increased air pollution monitoring and mitigation can help reduce. For example, reducing congestion can lower public health costs or improve productivity. Fighting asthma before attacks occur can improve school and work attendance. Understanding long-term costs and benefits can help your team build the case for a budget for air pollution monitoring and mitigation.

Many local leaders are developing creative new approaches. As an example, the Bay Area Air Quality Management District (BAAQMD), which regulates air pollution in nine counties around San Francisco, recently authorized (see slides #7-15) moving forward on a $6 million contract with Aclima Inc. to map the area's air pollution over the next two years. Aclima Inc. proposed to deploy its mobile air pollution sensor systems on vehicles throughout the Bay Area and make that data available to the public via an online portal that can help communities better understand local pollution patterns. BAAQMD plans to use these data to help target areas where further investigations are needed, potentially leading to better enforcement of pollution rules.

PART 02: NUTS & BOLTS

Designing hyperlocal air monitoring systems

This section walks through how to design hyperlocal monitoring systems. As you work through this resource, consider your starting point. With no air quality monitoring, it may make sense to start with a few high-quality, reference-grade monitors, particularly if your goal is to advance regulatory actions. Lower-cost stationary sensor networks and mobile mapping can supplement existing reference-grade equipment, or potentially serve as an alternative to reference monitoring systems for cities with more limited capacity. No matter where you are starting from, the monitoring strategy should be targeted to collect the kind of data that enables you to achieve the actions that motivate your monitoring.

In addition to using the guidance and examples in this resource, you should consult with expert partners who can help you design and implement monitoring systems and processes that meet your goals. These experts include:

Air pollution scientists:

They can provide critical expert advice on monitoring systems and methods that will meet your data objectives. These experts are often scientists in the field of environmental engineering, atmospheric science (chemistry, and/or physics) or environmental health science. While they often work in academic institutions, many also work at public agencies responsible for air quality management, or for private companies.

Local residents and community groups:

Community members can provide important insights on potential sources and areas of concern, and should be consulted during the monitoring design and planning phase.

Health scientists:

They can provide expertise in assessing the risk associated with pollutant exposure and needed context to fully explain the impact on public health.

Air monitoring systems providers and/or specialist consultants or contractors:

In addition to selling or leasing air monitoring systems, some companies also provide auxiliary services such as systems design and access to their in-house air pollution experts. Specialist consultants can help evaluate monitoring technologies, design and/or assess your monitoring systems, as well as create an appropriate data management system.

A team that includes these kinds of experts can ensure the project plan starts with a monitoring strategy that is suited for the health and climate goals motivating the project, and provides data fit for the purpose. They will also ensure the plan includes an ongoing data validation strategy that begins with ensuring the instruments are properly calibrated throughout the study period.

A. DEFINING MONITORING GOALS

Before you start designing your hyperlocal air monitoring system, you first need to define your monitoring goals. These goals will determine what pollutants to measure and the kind of monitoring data you need, which will inform the overall approach and design of your monitoring system. Common monitoring goals include:

1. **Identifying and characterizing an air pollution problem.** This can include understanding variation on the pollution concentrations across your city, identifying hotspots, discerning sources, and assessing adverse health impacts.
2. **Creating awareness and urgency around enforcement, a public health program, or an advocacy campaign.** You may want to document and make visible the pollution problem in your city — to make the invisible, visible; create momentum to advocate for local, regional or national policy or action; or build support for public investments in clean air.
3. **Using block-by-block data to fine-tune actions and policies.** This can apply to a) investigation and enforcement; b) emergency public health interventions; c) transportation planning and traffic management; d) zoning, permitting, building codes, and land use; and e) targeted investments and incentives for emissions-reduction projects.
4. **Assessing the impact of a policy action by measuring the pollution levels before and after an intervention.** Hyperlocal air pollution data can be used to iterate and improve policy actions, and making the data public increases transparency and accountability.

In addition to these primary objectives, you may find that you can also use your monitoring results to improve emissions inventories and air pollution models and forecasts, which further aid decision-making.

WHICH POLLUTANTS TO MEASURE?

Defining the pollutants of interest is a critical step in your monitoring design. The pollutants you choose depend on the source(s) of concern in your city, or those most relevant to your monitoring goal. Keep in mind that air pollutants have different physical properties, as well as different health impacts, which have implications for how best to measure and map them. For example, black carbon is a good marker for diesel combustion and is directly related to its source, which makes it a good pollutant to measure if you're interested in measuring the impact of diesel combustion on air quality with good spatial resolution. Black carbon also has important chronic and acute health impacts, and is a climate pollutant.

The pollutant(s) you want to measure will be driven primarily by the emission sources of concern. The table below provides a summary of "best fit" pollutants for different monitoring goals. These pollutants have been the focus of monitoring efforts by EDF and partners as they are relatively well-suited to hyperlocal monitoring, given that most are primary[4] pollutants and are closely related to their source. (Note: This is not an exhaustive list of pollutants of concern for these monitoring goals.)

Keep in mind that air pollutants have different physical properties, as well as different health impacts, which have implications for how best to measure and map them.

"Best Fit" Pollutants by Monitoring Goals

MONITORING GOALS	NO	NO_2	BC	$PM_{2.5}$	UFP	O_3	VOCS
1) Identify air pollution problem and assess severity	●	●	●	●	●	●	●
2) Create awareness and urgency		●	●	●	●	●	●
3a) Investigate and enforce*		●		●		●	●
3b) Implement emergency public health interventions		●		●		●	●
3c) Inform transportation planning and traffic management	●	●	●	●	●	●	
3d) Inform land use zoning, permitting, and building codes	●	●	●	●	●		●
3e) Direct or prioritize investments and incentives**		●	●	●	●		●
4) Assess air quality before and after a policy intervention***	●	●	●	●	●	●	●

Notes:
** Pollutants of interest for investigation and enforcement tend to be those that are regulated.*
*** Multiple pollutants likely of interest to better understand cumulative burden.*
**** Pollutants of interest highly dependent on what type of policy interventions are being assessed.*

Once you've set your monitoring goals and determined the pollutants of interest, you can then define your data objectives. These objectives describe what you want the data to tell you. The table below illustrates the types of data objectives that correspond to various monitoring goals. Your data objectives will determine what pollutant(s) you need to measure, the kinds of stationary and mobile monitors you'll use, and where to monitor. While it is possible that air monitoring results may be used to address more than one objective, prioritizing your data objectives will help ensure that your monitoring design can be directed to address the most important one.

Monitoring Goals and Data Objectives: Potential Use of Hyperlocal Insights

MONITORING GOALS	DATA OBJECTIVES
1) Identify air pollution problem and assess severity	• Quantify air pollution levels and characterize pollution patterns across the city or areas of interest
2) Create awareness and urgency	• Quantify air pollution levels and characterize pollution and associated health impact patterns across the city or areas of interest • Identify presence of pollutant(s) in excess of health benchmarks
3a) Investigate and enforce	• Identify unknown or suspected emission sources (hotspots)
3b) Implement emergency public health interventions	• Real time identification of acute levels of harmful pollutants with reasonable spatial accuracy • Real time screening for hotspots
3c) Inform transportation planning and traffic management	• Identify hotspots along road corridors or beside facilities • Quantify air pollution levels and characterize transportation related air pollution, health, and economic damages within the city
3d) Inform land use zoning, permitting, and building codes	• Identify unknown or suspected emission sources (hotspots) • Quantify air pollution levels and characterize pollution patterns across the city or areas of interest
3e) Direct or prioritize investments and incentives	• Hotspot identification • Quantify air pollution levels and characterize pollution patterns to identify most pollution burdened areas or understand relative pollution burden in different areas; identify areas and strategies with highest return on investments
4) Assess air quality before and after a policy intervention	• Quantify changes in concentration levels over time

Two major questions arise when you start designing your monitoring effort: What sensor systems should you use? and What monitoring approach should you take?

B. SELECTING MONITORING EQUIPMENT

The monitors or sensors you choose to add to your network will depend on the pollutant(s) you want to measure, the data quality you need for your monitoring objectives, and the budget you can devote to purchase and maintain the equipment (as well as managing and analyzing the data).

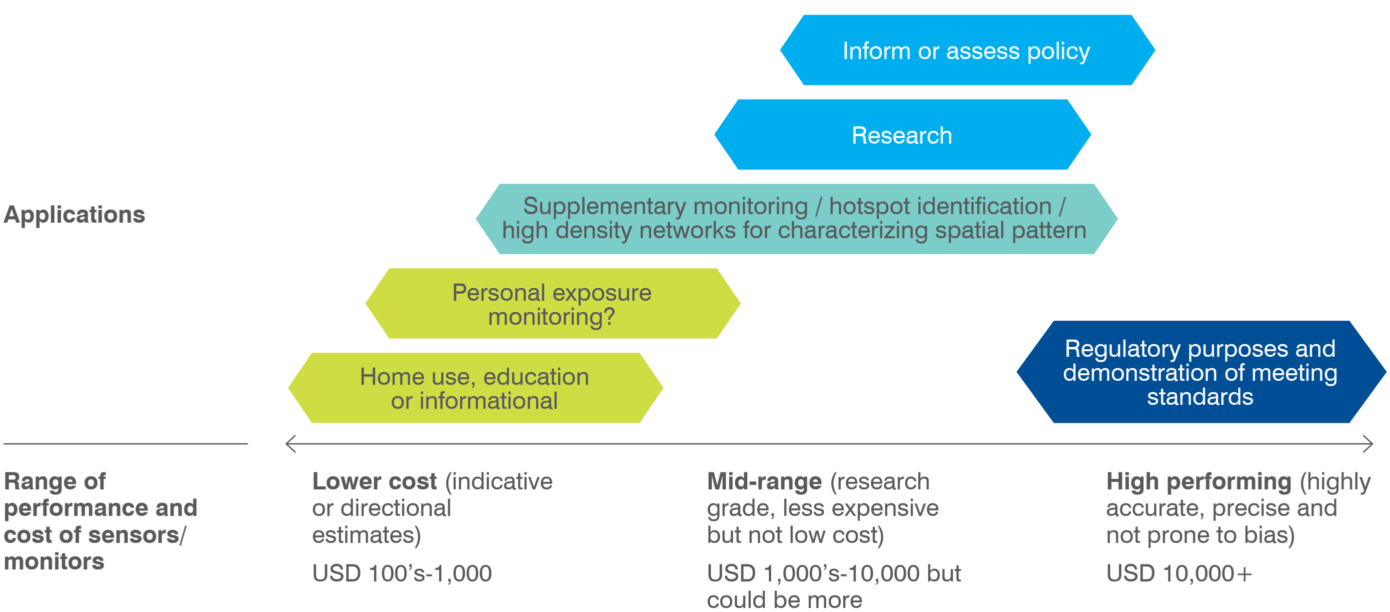
It is worth noting that the terms sensors, instruments, and monitors are often used interchangeably. For the purposes of this guide, we define them as follows:

Sensor: The basic hardware in a system that detects and measures a pollutant, but needs additional components (e.g. power, processor) to be deployed. There are also sensors that detect and measure meteorological parameters, which are often used in conjunction with pollution sensors.

Sensor System / Sensor Package: An integrated set of hardware that uses one or more sensors to detect and/or measure pollutants, process signals, and output parameters. These may or may not include visual displays, batteries for power, and ethernet or wireless internet. (Note: The terms "instrument" and "monitor" are often similarly defined and for the purposes of this guide we use these terms interchangeably with sensor system.)

Reference Monitor: Instrument operated and maintained according to initial and ongoing federal equivalent method (FEM)/federal reference method (FRM) and quality assurance (QA) protocols, often by a local, state, or federal government agency.

Examples of types of monitors and corresponding applications:



With a growing number of lower-cost air pollution sensors and sensor systems continuing to come into the market, regulatory agencies and researchers have been evaluating their performance. We recommend the resources below. For cost ranges, see the AQ-SPEC resource center listed below, which compiles cost estimates for a wide range of PM and gaseous sensor systems.

Air Pollution Sensor and Monitor Performance Evaluation

- U.S. Environmental Protection Agency Evaluation of Emerging Air Pollution Sensor Performance
- Air Quality Sensor Performance Evaluation Center (AQ-SPEC) by California South Coast Air Quality Management District (SCAQMD)

Also see more detailed guidance on factors to consider when selecting sensors or monitors in Part 2.2(A) System procurement.

C. CHOOSING A MONITORING DEPLOYMENT APPROACH

- Should you deploy a network of fixed sensors, mobile sensor systems, or both?
- For fixed networks: Where should you place stationary monitors? How dense should your network of monitors be?
- For mobile strategies:[5] What vehicles should you use for mobile monitoring, and where should they drive? How many times does a driver need to pass a location to characterize its pollution adequately?

The goal guides the design. For example, in the first mobile monitoring campaign in Oakland, CA, residents have long known that air pollution in their neighborhoods can differ significantly from levels shown by the few existing regulatory monitors. The main objectives for this monitoring effort was to understand how air pollution varies within the West Oakland community down to the block level and identify pollution hotspots. This meant covering every public street in the community including nearby likely pollution sources, such as metal recyclers, as well as quieter streets with no known sources. The sampling strategy sent drivers down every street of the study area multiple times over the duration of the study. Repeated passes, scheduled to create a balance of data in different times of day, days of the week, and months of the year, ensured that mobile data accurately captured spatial patterns of pollution.

A combination of dense, distributed stationary network and mobile monitoring can be used to help establish a more complete baseline of air quality before a policy intervention such as the Ultra Low Emission Zone (ULEZ). The combination of stationary and mobile monitoring ensured both temporal and spatial coverage of measurements that can be used to assess the changes in ambient air pollution concentrations. To assess conditions before and after the policy was implemented, monitoring started around six months before the ULEZ came into force in April 2019 and will continue through at least six months after.

If your goal is to identify patterns for health assessments or assess the before and after of a policy, you should ideally plan to monitor for a year, especially if your city experiences significant seasonal changes. Understanding variation by time of day is an important factor in understanding not just where, but importantly when, people are exposed to higher levels of pollution.

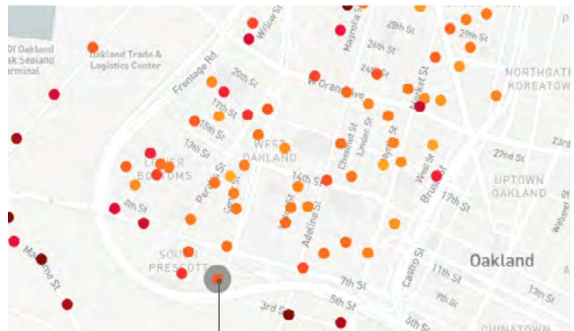
Hyperlocal air pollution mapping: stationary and mobile

There are tradeoffs between stationary monitors, which measure pollutants 24/7 at a fixed spot, and mobile monitoring, where the monitoring vehicles take measurements as they drive through the streets. Results from stationary monitors will have much higher temporal resolution, while results from mobile monitoring will generally give you a more complete and granular spatial coverage. In practice, a monitoring strategy could combine both mobile and stationary monitoring to get the best of both approaches.

BLACK CARBON MAP (FROM MOBILE MONITORING OVER ONE YEAR)
Map shows the median black carbon levels for the study period at every 30m in West Oakland.

BLACK CARBON MAP (THE '100x100' PROJECT)
A stationary monitoring network of one hundred Aerosol Black Carbon Detectors deployed for one hundred days in West Oakland). Maps show black carbon levels at 100 locations (6.7 sampling sites/km^2) at 8am and midnight on a Wednesday. The high temporal resolution nature of stationary monitoring data allows us to see how air pollution changes over time.

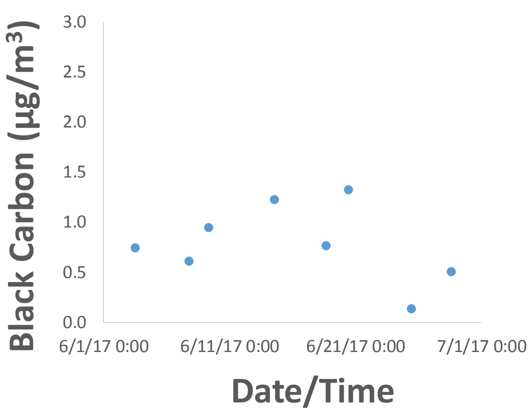
Space

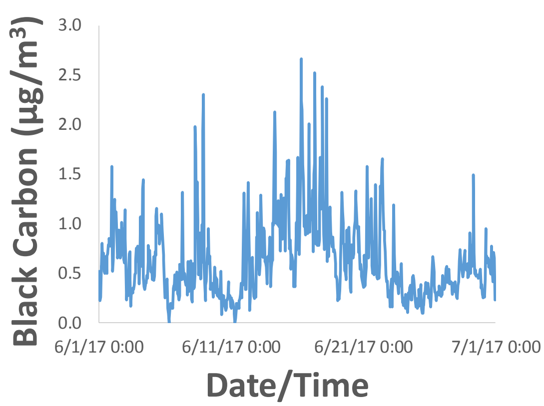


Higher spatial resolution

Lower spatial resolution

Time





Lower temporal resolution

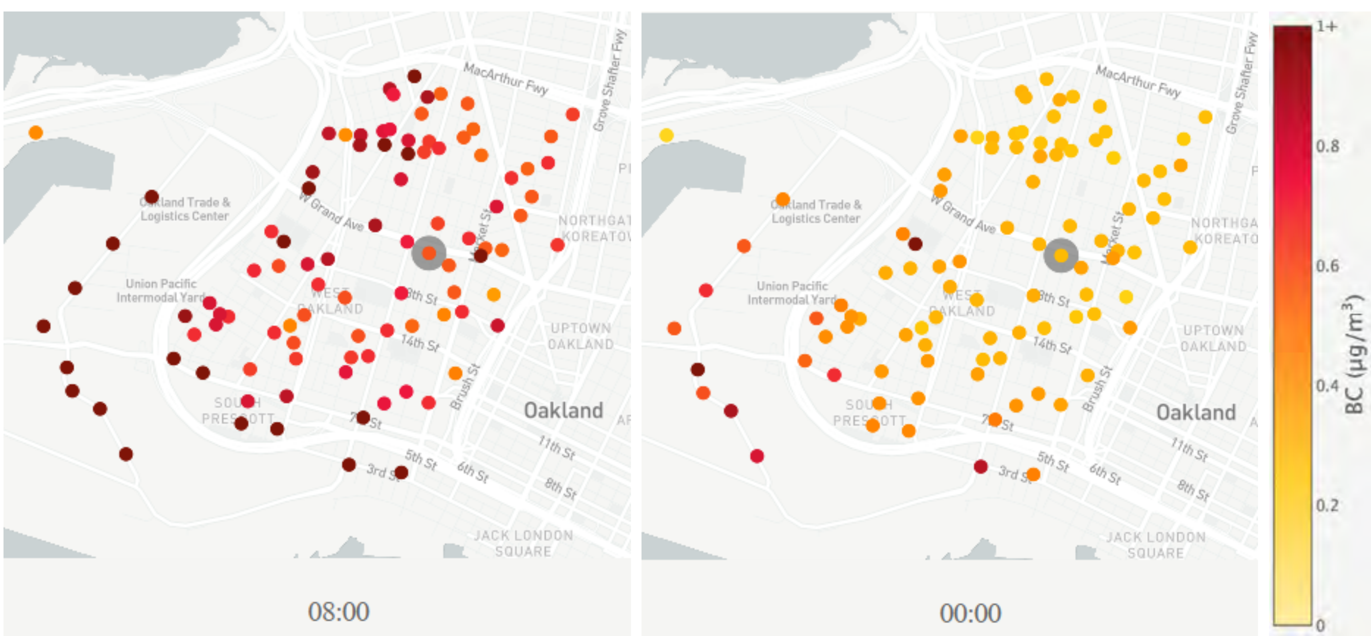
Higher temporal resolution

For instance, in Oakland, our mobile monitoring results rendered a detailed picture of black carbon and nitrogen oxides (NO_x) concentrations at every 30 meters. The resulting map approximates annual average pollutant levels during the daytime sampling periods. While this initial map allows users to see fine-grained pollution patterns, it can't show which month, day of the week, or time of day pollution is at its peak. To better understand the temporal variations, a subsequent study placed black carbon sensors at 100 locations for 100 days. While the map produced by this study is not as highly spatially resolved, the data answer questions about how pollution levels change across different time periods, in a way that the mobile monitoring could not.

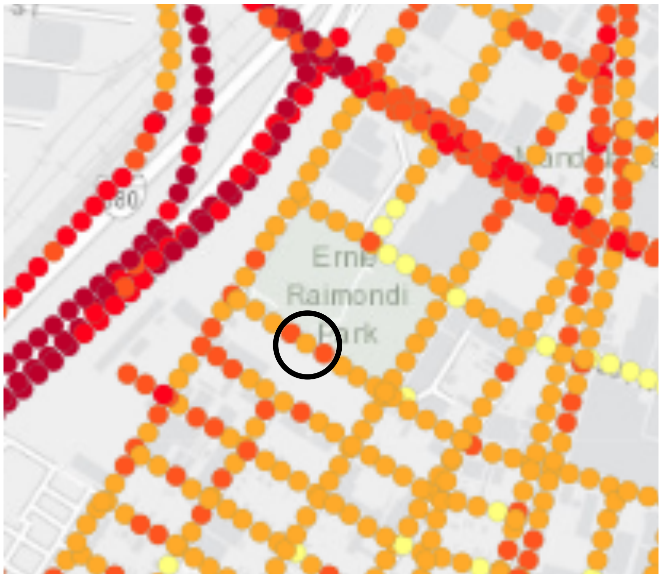
BLACK CARBON MAP FROM MOBILE MONITORING OVER ONE YEAR. MAP SHOWS THE MEDIAN BLACK CARBON LEVELS FOR THE STUDY PERIOD AT EVERY 30M IN WEST OAKLAND.

BLACK CARBON MAP FROM THE '100X100 PROJECT', A STATIONARY MONITORING NETWORK OF ONE HUNDRED AEROSOL BLACK CARBON DETECTORS DEPLOYED FOR ONE HUNDRED DAYS IN WEST OAKLAND.

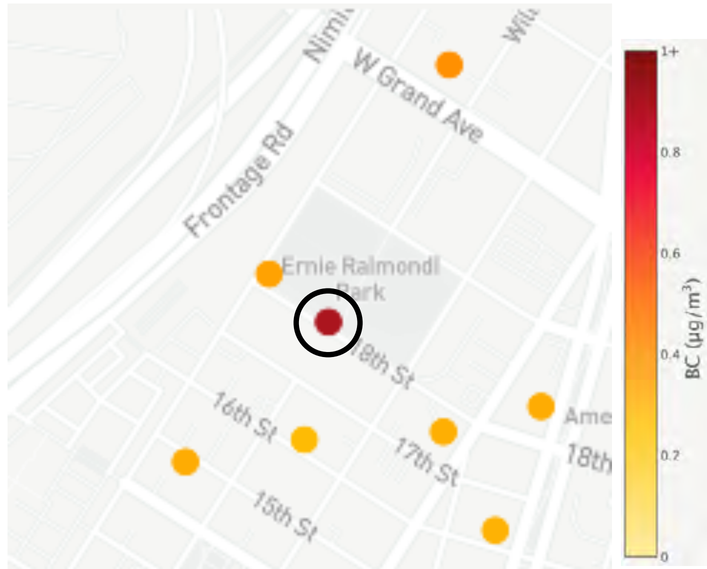
Maps show black carbon levels at 100 locations (6.7 sampling sites/km^2) at 8am and midnight on a Wednesday. The high temporal resolution nature of stationary monitoring data allows us to see how air pollution changes over time.



In addition, mobile data is often collected during the daytime, as was the case in Oakland, where the cars drove from morning to early evening. In contrast, stationary monitoring networks can collect data continuously. For example, in our 100x100 study, a monitor directly downwind from a trucking company across the street from a sports field tracked pollution patterns that rose at nightime, increasing exposure for people playing at the field. While this hotspot appeared in our stationary network data, it was not evident in our mobile air monitoring data as the mobile platforms were only deployed during the daytime. This is illustrated by the comparison of the two maps below.



Median daytime black carbon concentration
from mobile monitoring



Average black carbon concentration at 2:00am
from stationary monitoring

Hyperlocal mobile monitoring can be more useful for screening given the comprehensive spatial coverage of resulting pollution maps. The two monitoring types can work together in stages, with mobile monitoring results being used to inform where to place stationary monitors through identifying locations of concerns or emission sources not previously known.

Stationary monitors can be a more cost-effective option in areas where you expect less variation in air pollution, or where you have a better idea of where the emission sources or problem areas are.

Other trade-offs between stationary and mobile monitoring include cost and relative ease of deployment. Building a dense (or denser) stationary monitoring network can be more feasible for a city considering an initial investment in air quality monitoring. Low-cost stationary monitors have become easier to find in recent years and their performance is improving. While mobile monitoring can provide greater coverage, and a more granular picture, it can be a time- and resource-intensive undertaking to set up and manage dedicated mobile platforms.

Stationary monitoring design considerations for hyperlocal air pollution mapping

Your goals — which may range from detecting and assessing pollution levels around a suspected source, quantifying how pollution affects homes and schools, or assessing the effect of a policy that aims to improve air quality — will guide where you site your monitors.

Main siting considerations include:

- What is your geographic area of concern?
- Where are the pollution sources of concern? Or, where do you suspect pollution might be a problem based on public complaints, poor compliance history, land use, or other local knowledge your team may have gained from experience?
- Where do people live, work, play, and go to school?
- Where do sensitive populations spend time?

Other air monitoring resources you may also want to review about stationary monitoring design and siting:

- U.S. Environmental Protection Agency Air Sensor Toolbox
- Greater London Authority Guide For Monitoring Air Quality in London
- Guidebook for Developing a Community Air Monitoring Network by the Imperial County Community Air Monitoring Project

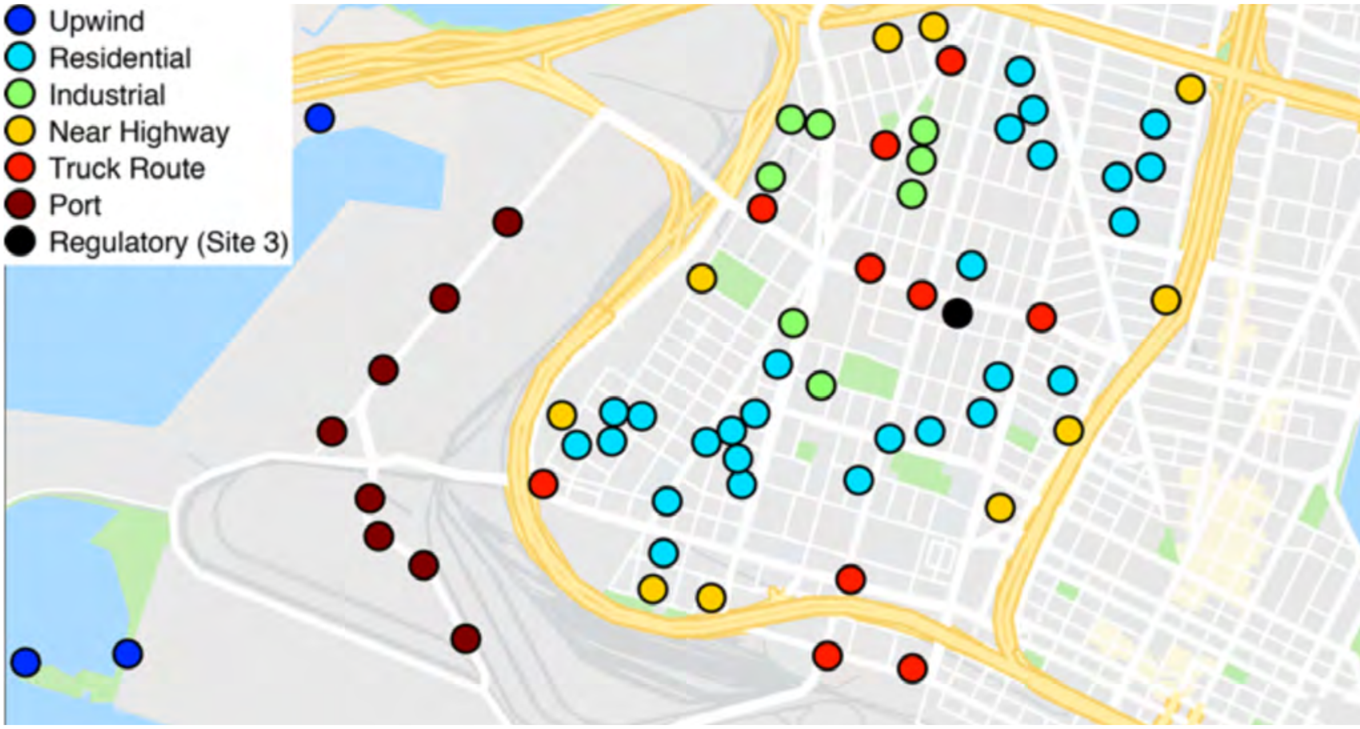
In the 100x100 monitoring project in West Oakland, project partners — guided by advice of local residents and community leaders — placed 100 black carbon sensor package in 100 distinct locations in a 15km^2 area of West Oakland neighborhood. Sensor placement was designed to:

- Distribute sensor packages evenly (or as evenly as possible) throughout neighborhoods to characterize differences in black carbon levels in different parts of the community
- Capture a variety of conditions and potential sources (e.g. the main road serving the Port of Oakland, designated truck routes, prohibited truck routes, residences on quieter streets, and known or suspected sources) to determine what was causing harm to whom
- Sample at locations upwind of local sources to serve as a proxy for regional background pollution levels
- Assess whether the sensors were adequately calibrated by deploying them at or in close proximity to the existing regulatory monitoring station in the area

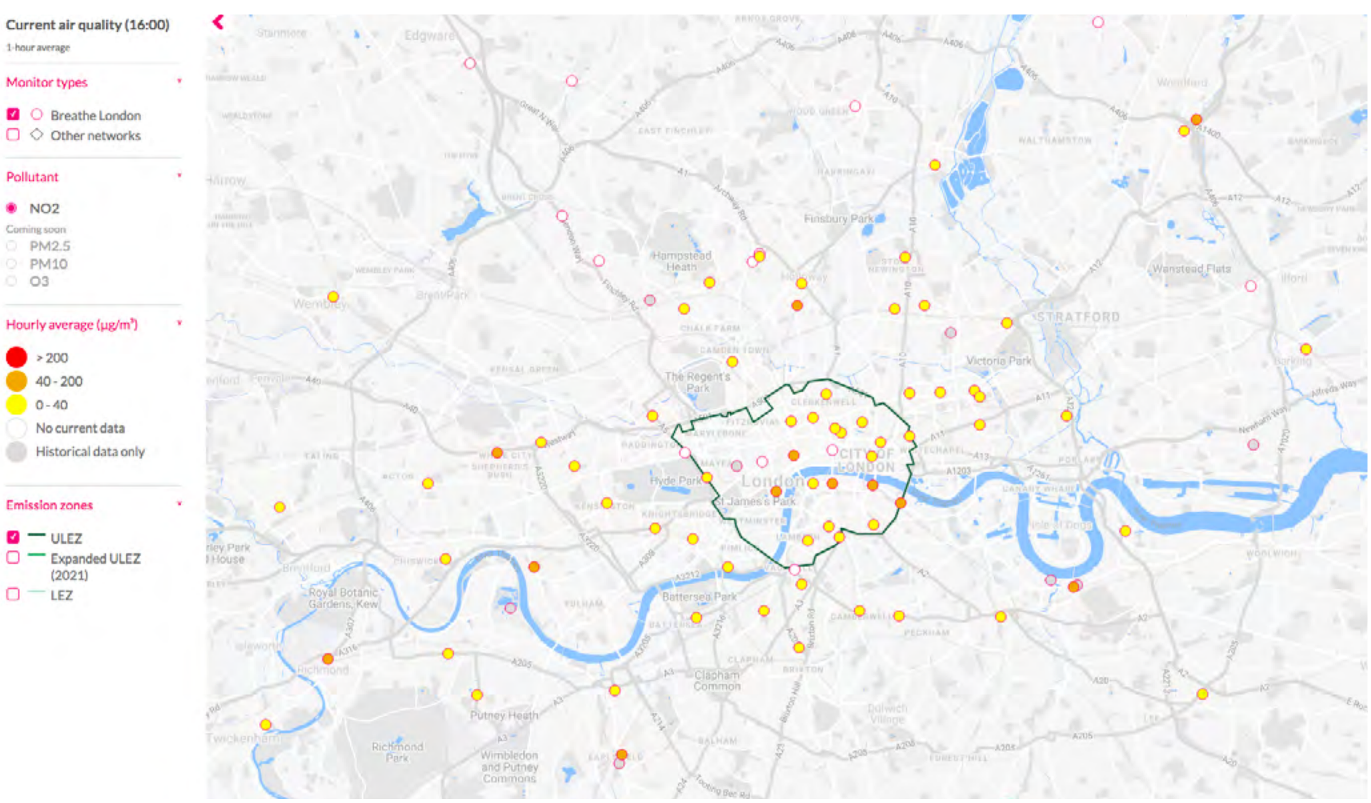
In London, sensor pod location placement was intended to:

- Cover all 32 London boroughs plus the City of London
- Fill gaps in the existing network of government air quality monitors
- Place priorities on sensitive locations, such as primary schools and medical facilities
- Support assessments of the impact of new policies designed to reduce air pollution, such as the Ultra Low Emission Zone (ULEZ), the Expanded ULEZ, and the Low Emission Bus Zones (LEBZ)
- Distribute sensor packages across a mix of traffic levels and at varying distances from major roads and intersections, parks, residential areas, high-traffic streets, and other commercial areas
- Co-locate pods, over long-term or periodically, alongside reference monitors for performance evaluation

MAP SHOWING DIFFERENT TYPES OF SITES WHERE BLACK CARBON SENSORS ARE LOCATED IN THE 100X100 WEST OAKLAND SENSOR NETWORK.[6] (NOTE: SOME LOCATIONS WERE NOT CATEGORIZED AND ARE NOT SHOWN ON THIS MAP)



MAP OF BREATHE LONDON STATIONARY SENSOR NETWORK.



If there is a consistent prevailing wind direction in the area you are monitoring, it is good practice to place some monitors upwind of the area you are monitoring to serve as a proxy for background pollution levels that are not affected by local sources. This can help you better distinguish the effects of local sources. In addition, place your monitors at sites that are representative of what you are trying to measure. If you are trying to gain a broad understanding of how air pollution varies across your city, try to achieve an even spatial distribution.

Once you have the high-level plan of where you want to site your sensor systems, there are many site-specific details you'll need to consider. These are covered in Part 2.2(C) Instrument deployment, operations and maintenance.

Mobile monitoring design considerations for hyperlocal air pollution mapping

Mobile monitoring can measure and map the variations in pollution levels at scales ranging from 30 to 150 meters, much finer than most stationary monitoring networks. However, each measurement is a snapshot in time of pollution at a certain location. To create a stable, robust, and representative picture of pollution at any one location over time, you need to take repeated measurements.

Different kinds of vehicles can serve as mobile monitoring platforms. In most of our projects, EDF and partners have employed dedicated monitoring vehicles (primarily Google Street View cars) whose only job is to collect data. This level of support can be resource intensive, involving the need to buy or rent vehicles, hire drivers to systematically drive preset routes, coordinate closely with drivers on a daily basis, and manage a host of other logistical details.

The key advantage to employing dedicated monitoring vehicles is that you have more control over how, where, and when data is collected. Professional drivers can drive extensively in a certain territory, providing you with a comprehensive, responsive, and directed data collection. As discussed in the Mobile Dedicated Sampling Strategy box, sampling method is an important factor in controlling for potential biases in the resulting dataset. Additionally, in our projects with a dedicated monitoring fleet, we have used higher-cost (research grade or near reference grade) monitoring systems, which have greater accuracy and precision than lower-cost systems. However, this requires dedicated resources such as specialist contractors to support daily operations and carry out routine maintenance of the sensor systems.

Sample size

The more frequently you collect measurements on each road segment, the larger the sample size you will have to tease out any patterns in the pollution levels within the monitoring area. For our Oakland project, the research team purposely oversampled by having the monitoring vehicles drive every road between 20-50 times on average in the first year of data collection.[7] Further analysis found that we could reach a point where aggregated measurements became stable with fewer than 30 repeated drives. Generally, EDF aims to collect measurements on each street in a study area between 15 and 20 times in order to find a central tendency. However, there is no single magic number of repeated drives; it will likely vary for each mobile monitoring effort depending on the inherent variability in the pollution within a city and the instruments used --which depends on factors discussed earlier including instrument's response time, accuracy, and precision, among others. The ideal and minimum number of repeated measurements also depends on the uncertainty you can tolerate for the decision or analysis you hope to make, your other sources of data, and the financial and time resources you can spend.

Alternatives exist to the reliance on dedicated data collection vehicles. If you can reach your data goals without driving special routes, you may be able to use vehicles from your existing city fleet, such as sanitation trucks, parks department, utility, or health department vehicles. In this scenario, a project manager would examine the drive histories of the fleet and select the vehicles that offer the best combination of repeated passes over road segments of interest and coverage of the city.

EDF's Future Fleets report describes how this analysis works. Our analysis found that a fleet-based monitoring approach — where drivers drive their regular routes, doing their regular jobs — can achieve substantial coverage of a city in a few months time by equipping just a few of the right vehicles.

The City of Houston and EDF partnered to pilot this approach by leveraging Houston municipal vehicles equipped with simpler, lower-cost sensor systems. The sensor systems are designed for easy installation on top of municipal vehicles, and their functions are streamlined to minimize the time and skills drivers need to operate them. At the end of the day, drivers may at most need 10 minutes to recharge instrument batteries, or perform simple checks. This lower-cost monitoring approach was able to detect elevated levels by a school, park, and industrial facility that would not have been evident from regional monitoring. Fleet-based data collection may not identify every potential hotspot and lower-cost instruments may not be suitable for mobile measurement of some pollutants. However, this approach is much less resource intensive.

These roles and expertise can help plan a mobile monitoring strategy:

Air quality experts and data scientists advise on an optimal monitoring design that corresponds with the planned analysis, and to periodically check to determine if the initial plan will result in sufficient measurements to inform that analysis.

Local residents and community groups provide important insights on potential sources and areas of concern, and should be consulted during the monitoring design and planning phase.

Project coordinator(s) for mobile monitoring efforts identify the right vehicles, train drivers, manage instrument providers, and work with experts and the driving team to develop a day-to-day driving plan.

Mobile Dedicated Sampling

Strategy

To ensure complete and systematic coverage of your monitoring area, it is helpful to divide it into subsections or polygons such that all the streets can be covered by a vehicle in no more than 2-4 hours. Factors to consider in your plan include:

- Sampling bias will be minimized if you rotate the schedule so that all polygons get sampled evenly across different times of day and different days of the week.
- Traffic congestion will affect how much ground can be covered each day. You may need to consider the trade-off between repeat visits to certain locations (more data points at one place, but fewer locations) and obtaining larger spatial coverage (fewer data points at one place, but more locations).
- Drivers' work shifts.
- Distance between the vehicle's home base and the sampling areas.
- Collection of data across seasons to account for different meteorological conditions as well as emission sources and activities that change across seasons.
- Oversampling in particular areas such as known or suspected hotspots.

Note that the sampling strategy discussed here is applicable to the use of a dedicated fleet of monitoring vehicles, where you are able to direct the driving schedule and control when and where to sample. This allows you to constrain the temporal bias and prevent scenarios where you sample certain locations only at certain times or days. Ensuring a balanced and robust sample is important for the ability to produce a meaningful central tendency, which allows you to discern the true differences in pollution levels between locations. See Part 2.3 Making Sense of the Data for further discussion on central tendency method.

mobile monitoring, or both?

The table below provides examples of where to use stationary, mobile, or both kinds of monitoring approaches depending on your monitoring goals and data objectives. In addition to a distributed stationary network or comprehensive mobile monitoring that provide a wide-net area coverage, cities may also combine different kinds of monitoring in sequence. For instance, cities may use broad-based mobile monitoring to decide locations of interest where their movable or short-term stationary monitoring platforms should stop to take measurements, or where to deploy fixed sensors.

MONITORING GOALS	DATA OBJECTIVES	"BEST FIT" MONITORING APPROACH
1) Identify air pollution problem and assess severity	• Quantify air pollution levels and characterize pollution patterns across the city or areas of interest	**Dense, distributed stationary network or comprehensive mobile monitoring,** depending on the spatial resolution you hope to achieve and resources available.
2) Create awareness and urgency	• Quantify air pollution levels and characterize pollution patterns across the city or areas of interest; • Identifying presence of pollutant(s) in excess of health benchmarks.	**Dense, distributed stationary network, providing real-time** air pollution information as an effective tool to create a sense of urgency and increase awareness among the public. In addition, **both stationary and mobile monitoring** data can feed into health assessments which can contribute to the same goal.
3a) Investigate and enforce	• Identify unknown or suspected emission sources (hotspots)	**Comprehensive mobile monitoring** to detect hotspots. Mobile monitoring is a more effective screening tool given the high spatial resolution of resulting data. Once detected, movable monitors could be deployed at hotspots to monitor pollution levels over longer term (air quality dashboard overview). **Targeted stationary monitoring** can also be employed where locations of suspected sources are known.
3b) Implement emergency public health interventions	• Real time identification of acute levels of harmful pollutants; • Real time screening for hotspots	**Targeted stationary or mobile monitoring, providing real-time data.** Stationary sensor systems can be deployed at known or suspected sources to detect elevated levels during high emission events (e.g. fenceline monitoring around industrial facilities). Mobile monitoring deployed to areas of concern during or immediately after high emission events (e.g. following industrial disasters). (See also emergency response monitoring case study)
3c) Inform transportation planning and traffic management	• Identify hotspots • Quantify air pollution levels and characterize pollution patterns along roads and streets, including some time of day variation	The **type of monitoring approach needed will depend on the transportation measure(s)** being considered. For instance, interventions to reduce vehicular emissions such as Low Emission Zones or Congestion Charge Schemes cover large geographic areas and are likely to require a more extensive monitoring approach, whether a distributed stationary network or comprehensive mobile monitoring in the relevant area, to inform the planning and/or evaluate efficacy. More local level interventions such as speed limit reduction, traffic restriction, traffic reallocation, and placement of active transportation infrastructures such bike lanes, could potentially be informed by targeted, or semi-distributed stationary monitoring network (e.g. along certain road corridors). Targeted stationary monitoring may also be useful for enforcement activities such as compliance of no-idling or clean engine rules.

MONITORING GOALS	DATA OBJECTIVES	"BEST FIT" MONITORING APPROACH
3d) Inform land use zoning, permitting, and building codes	• Identify unknown or suspected emission sources (hotspots) • Quantify air pollution levels and characterize pollution patterns across the city or areas of interest.	**Comprehensive mobile monitoring** can provide a more complete picture of the spatial variability in pollution, with a greater ability to detect unevenly distributed local emission sources or hotspots. This type of mobile monitoring is particularly suited for denser urban areas with mixed land use patterns. A complete picture of air pollution patterns across the city could inform new development planning (e.g. siting housing and sensitive receptors away from high pollution areas), re-zoning/re-permitting, or the creation of appropriate buffer zones between emission sources and where people live, work, and play. Highly granular data can inform building codes or site-specific interventions (e.g. requiring air filtration systems or green barriers in highly polluted residential areas). **Targeted deployment (either stationary or mobile monitoring)** at known or suspected sources can also inform re-zoning/re-permitting decision at those specific sites.
3e) Target investments and incentives	• Hotspot identification • Quantify air pollution levels and characterize pollution patterns to identify most pollution burdened areas, or understand relative pollution burden in different areas	Spatially granular air pollution data can help direct funding for emission reduction measures (e.g. vehicle replacement funds, zero-emissions zones, clean bus/truck funds, air filtration systems) in a more targeted fashion. **Multiple types of monitoring approaches** could be employed depending on the geographic scope of concern.
4) Assess air quality before and after a policy intervention	• Quantify changes in concentration levels over time	**Multiple types of monitoring approaches** can be used depending on the type of policy intervention being implemented. For instance, to evaluate the impact of Low Emission Zones, both distributed stationary monitoring network and extensive mobile monitoring may be needed. Justifying investments in clean technology such as a zero-emission bus fleet may warrant targeted stationary monitoring along key bus routes and at a bus depot.

Ready, set, go: Turning on and maintaining your network

This section lays out how to operationalize your monitoring plan — from procuring, installing, and testing your new monitoring equipment, to the day-to-day operations of hyperlocal air pollution mapping, to managing the data feed. It provides guidance on how to ensure the data you collect fits your purpose, and that you have the appropriate capacity and expertise on your team to complete the project. This guidance draws from EDF's and our partners' experience of conducting large-scale monitoring projects in multiple cities.

Hyperlocal air pollution monitoring efforts require a wide range of expertise and roles to design and install the equipment and software and to maintain them on a day-to-day basis. Key expertise and roles are listed below; more specific functions are highlighted throughout the rest of this section:

Air monitoring systems providers

are companies that only sell or lease air monitoring instruments as well as full-service contractors who work with you on systems design, instrument installation and maintenance, and provide and maintain a data management system. You might also consider collaborating with researchers or other technical partners with existing instruments.

On-the-ground technical support team

provides critical operations and maintenance support such as calibration and checks of the monitoring systems, on-going oversight of the instruments' performance, and troubleshooting various technical issues that can arise throughout your project. This level of support has been particularly crucial for mobile monitoring effort using dedicated vehicles, but may be less necessary for instruments that require little calibration.

Specialist consultants or contractors

help evaluate monitoring technologies, design and/or assess your monitoring systems, set up a data management system, and potentially perform analytics. The range of services available will differ from contractor to contractor.

Day-to-day project manager(s) and coordinators(s)

play critical roles in managing and coordinating the numerous aspects of hyperlocal monitoring efforts. Their roles include liaison with and between contractors and other partners, planning, meeting facilitation, outreach and stakeholder engagement, and troubleshooting.

Data scientists or analysts

help analyze, synthesize, and interpret air pollution data. They also play an integral role during the data collection phase to continually assess the data quality. It is especially helpful to work with data scientists or analysts with spatial and statistical modeling skills.

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.

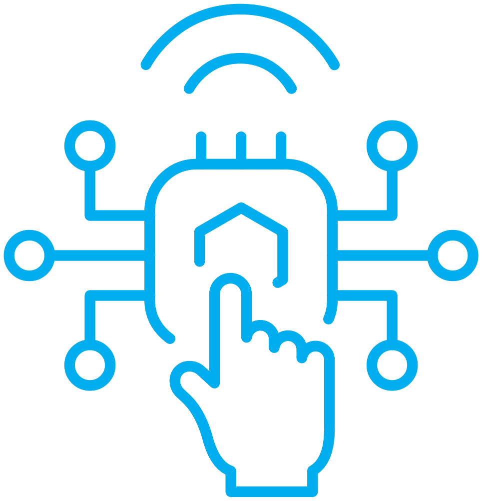
Testing environment.

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.

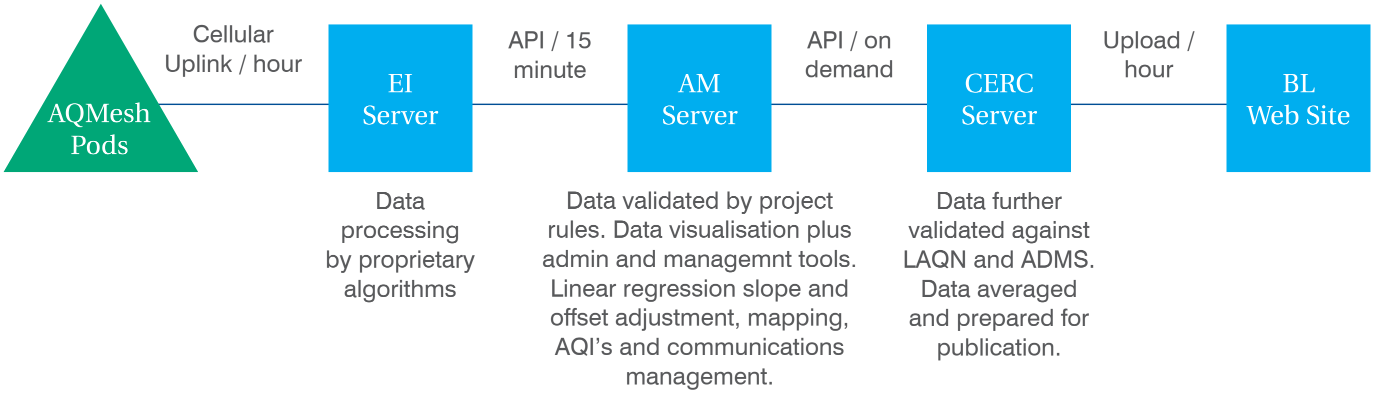
For more information on Breathe London project's data verification and quality assurance process, see the website's Methodology page.

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.

DATA QUALITY ASSURANCE AND QUALITY CONTROL (QA/QC)

It is important to establish robust quality assurance and quality control procedures for cleaning your data. Make sure you have a document that clearly charts your QA/QC procedures. This means interrogating each step in the data collection and processing to identify and correct possible errors. This is important for ensuring your data is properly quality controlled. It also ensures transparency, by allowing others to trace the path of your data from raw to final which is important in making the data useful for policymaking and inspiring trust from policy-makers, researchers, and the public. Work with air quality experts and data scientists to ensure your data processing plan will generate the quality level required for your data objectives.

QA/QC procedures will vary for different instruments, pollutant species, and operating condition requirements. Because no two monitoring systems are alike (different instruments, monitoring methods, and different monitoring goals), data QA/QC will differ from project to project. However, key procedures in data QA/QC generally include:

- Data acquisition.
- Quality/parameter checks (automated and manual).
- System flags (common flags include invalid measurements, missing data, measurements below/above detection limit, zero/span checks, instrument repair period).
- Date and time stamp.
- Spatial coordinate stamp, if mobile (check for invalid or missing GPS stamp). As mentioned earlier in Section B, ensure that every record uses a common time stamp that's based on a GPS satellite grade clock. You may need to apply time adjustments to the data, based on time of flight (when monitoring car takes off and begins data collection) and response time of sensor system.
- Other special flags, such as weather conditions that may affect measurements such as fog or extreme temperatures, and other anomalies and outliers.

Data QA/QC procedures should clearly articulate each step where data is processed (i.e. when data is redacted, adjusted, or transformed). For an example, see the summary of Breathe London project's data verification and quality assurance process on the website's Methodology page.

EDF has also developed a code repository for efficient data processing. Examples of open-source scripts we currently use can be accessed here.

Potential pitfalls and other important factors:

- It is important to have clearly articulated data QA/QC procedures at the outset of the project *and* to identify the responsible party for the various steps. Without an effective QA/QC plan, you may end up with erroneous data that have to be discarded and can't be retrieved.
- The development of a data QA/QC plan can often be iterative. As data is collected and reviewed, you may find errors not previously captured and that additional procedures and flags are required.
- Make sure to review the data sufficiently often. Data QA/QC systems usually have automated components, however, manual checks are also critical. Make sure these are carried out regularly.

Implementation readiness checklist

- ☐ Project team assembled; external partners have signed MOU(s)
- ☐ Partners agree on roles, responsibilities, and processes for making decisions and identifying/resolving problems; project goals, data objectives, and appropriate data deliverables established
- ☐ Funding secured
- ☐ RFP(s) for monitoring system design, testing, installation, and management issued
- ☐ Instrument provider and/or specialist service provider retained
- ☐ Instrument systems tested and verified in the field at an acceptable level
- ☐ New monitors co-located with reference monitors; results show agreement
- ☐ SOPs for instrument operations (including a troubleshooting resource for drivers) developed and easily accessible for all relevant groups
- ☐ Data management system in place
- ☐ Data QA/QC protocol in place

Making sense of the data

In pursuing hyperlocal air pollution mapping — whether you deploy a large, dense, stationary monitoring network, or measure pollution with mobile platforms — you'll be managing a large amount of data. The 100x100 black carbon sensor network deployed in West Oakland collected more than 20 million lines of 1-minute data over the course of 100 days. The Houston mobile monitoring project generated almost 33 million valid pollutant data points over the course of nine months. Data processing of these large datasets involves, primarily, data aggregation and data reduction using specialized algorithms. Data analysis is then carried out to identify detailed spatiotemporal trends, or how air pollution levels vary over space and time.

The expertise and roles that are essential to analysing hyperlocal air pollution data include:

Data scientists, analysts and/or modelers

who ideally specialize in environmental data. These are professionals with the capabilities to analyze and synthesize large amounts of data using a range of programs. It is recommended that you work with data scientists/analysts/modelers who are proficient at geospatial analysis, as the geographic or locational component is key in hyperlocal air pollution mapping.

Air pollution experts or scientists

who provide expert advice in guiding analysis. These experts and scientists with intimate knowledge of air pollution can advise on factors critical to analyzing air pollution data, such as impact of meteorology, wind direction, air dispersion, etc. They are often scientists in the field of environmental engineering, atmospheric chemistry, atmospheric physics or air pollution transport.

Individuals with local knowledge of air quality sources and concerns

such as local community partners, community leaders and residents, or researchers with in-depth knowledge on the air quality concerns in a particular area. Local insights are extremely valuable in informing data interpretation.

STATIONARY MONITORING DATA ANALYSIS

For end users to make sense of the large amount of data, the team must aggregate and present individual measurements in meaningful ways. For instance, the Breathe London team aggregates one-minute NO_2 measurements to hourly average concentrations which appear on the Breathe London air quality map.

Similarly, the 100x100 team aggregated black carbon sensor data from millions of 1-minute measurements to hourly average black carbon concentrations. This resulted in each of the 100 sampling sites having 2400 hours of data (24 hours x 100 days).[9] The team compiled the dataset on a visualization tool that allows for the exploration and analysis of black carbon concentrations across different time periods.[10] Data were analyzed to show hourly average black carbon levels at each monitoring site throughout the campaign period, or to see black carbon levels on a certain day of the week, or to compare levels on a weekday versus weekend. The results, embedded in the visualization tool, enable users to query the dataset to reveal different spatial and temporal patterns of air pollution.

MOBILE MONITORING DATA ANALYSIS

To render millions of data points collected from multiple months of mobile monitoring into a comprehensive air pollution map requires a deep and robust analysis. Below, we outline the basic steps that would allow you to conduct the sorts of analysis that EDF and partners have used in our hyperlocal mobile monitoring efforts. This analytical approach builds on a prior body of research.[11]

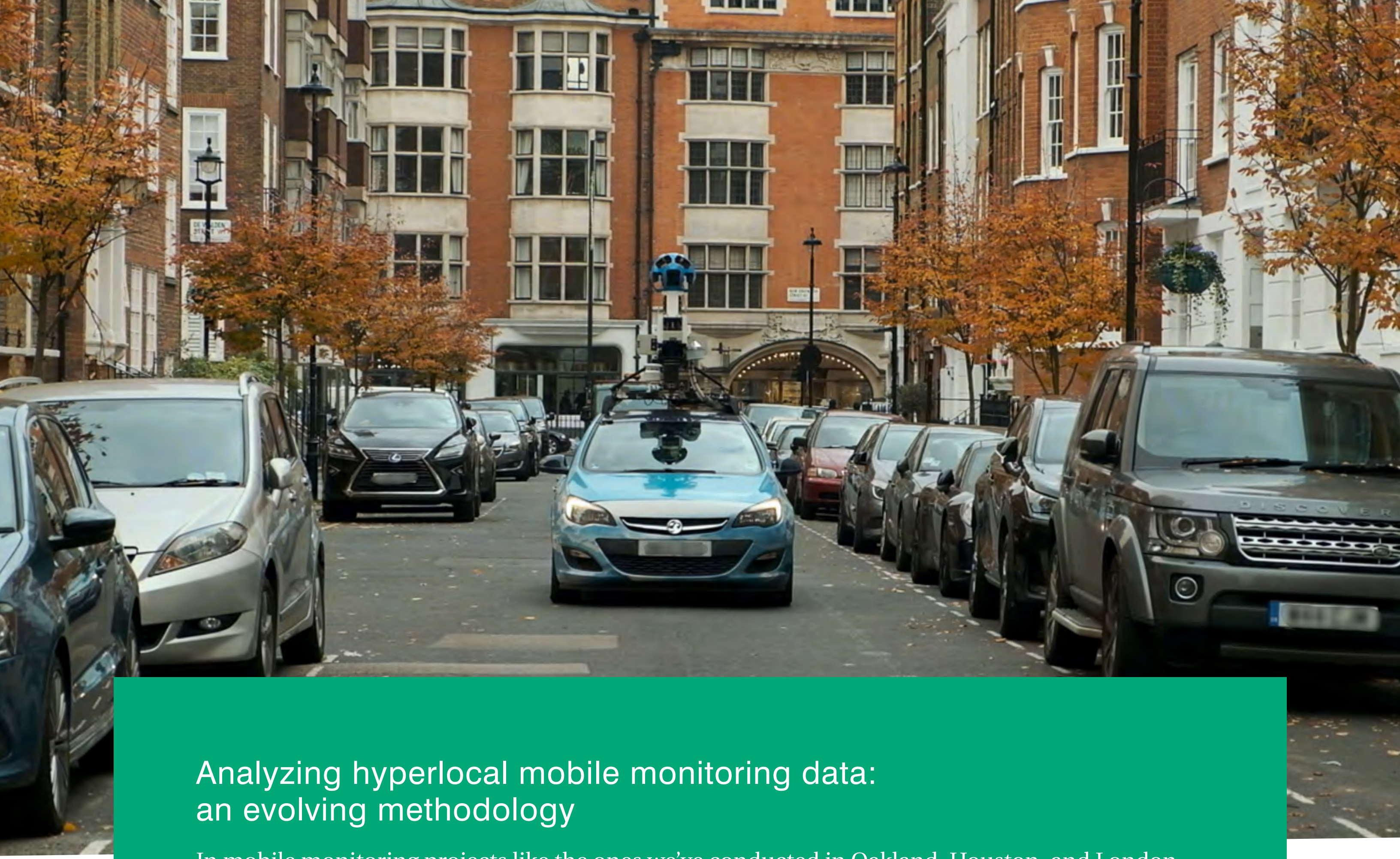
The analysis can generally be broken down into four major parts:

1. **Geolocation:** The process of assigning each air pollution measurement to uniform road segments ("grid-snapping"). The road segments should be of a uniform length to allow for an equal basis of comparison between segments. The length of road segments is based on what is appropriate for the speed of monitoring vehicles and instruments' response time. Ultimately, the level of spatial resolution (that is, how granular a map you can generate) will depend on the response time of the instruments.

2. **Assessing coverage:** Once you've assigned your air pollution measurements to the grids/road segments, you count them. You want to maximize the coverage, i.e. the number of drive passes over any road segment, that your budget allows. Each measurement represents a snapshot in time, and you will want as many drive passes in different conditions (weather, background pollution levels, etc.) as possible, so you can get a representative average. The number of drive passes (or air pollution measurements) you end up with in your grid/road segments will determine the uncertainty level of your dataset. With more drive passes, the effects of anomalous events are smoothed out, resulting in a more representative dataset.

3. **Finding the "central tendency":** Involves statistical analysis to establish a measurement value that adequately represents the pollution concentration over a longer period of time (e.g. yearly or a multi-month monitoring campaign). Colloquially, you could think of it as a steady average or long-term average air pollution concentration at a particular grid/road segment. Options for representing central tendency include an average, a midpoint (a median), or the midpoint of many results that occurred close together. For example, in Oakland, mobile monitoring platforms collected about 200 unique observations for each 30-meter road segment. The pollution maps were generated by first calculating the average concentration within each 30-meter road segment during each drive pass, and then calculating the median of averages across multiple drive passes for that 30-meter segment. This algorithm reduces the influence of individual extreme samples if, for example, a monitoring car happened to be driving behind a truck during one pass of a street.[12]

4. **Identifying hotspots:** Hotspots are the areas where the central tendency values are elevated compared to a reference value. Hotspots can be defined in multiple ways and will depend on the insights or actions for which the data is intended. For instance, you may want to identify the areas on the map where pollution concentrations tend to be above a certain threshold. You might compare the central tendency values (e.g. average black carbon concentration at a spot) with a chosen baseline concentration level. Generally this is done as a fraction, with the central tendency as the numerator, and a relevant baseline as the denominator, seeking those locations with fractions greater than one. Teams can use a neighborhood, a defined area, or a citywide average pollution level as the baseline. For example, in our initial Oakland work hotspots were defined as locations where concentrations of multiple pollutants exceed nearby ambient levels by 50% or more.[13] In order for the spot to be considered elevated, the uncertainty around the central tendency value should not have substantial overlap with the uncertainty around the baseline value.



Analyzing hyperlocal mobile monitoring data: an evolving methodology

In mobile monitoring projects like the ones we've conducted in Oakland, Houston, and London, we generated a huge amount of data. For instance, in Oakland, the monitoring cars drove more than 14,000 miles of roads for more than 150 days, collecting data every second. This generated more than 3 million data points. As discussed above, we used data science to map each individual data point, representing one second of pollution observations at a specific location, to a corresponding 30-meter length of road. This algorithm allowed us to turn millions of data points into a map like the one shown below. The initial analytical method used in Oakland was published in a 2017 peer-reviewed paper.[14] A summary of this methodology can be found on EDF's website.

In Houston, our team updated the algorithm to calculate and more precisely reflect the actual distance a car travels between measurements, while previously we had used 30-meter distances in the Oakland project which was based on average car speed and instrument response time. This improved method better reflects the real world conditions under which data is collected. The methodology continues to evolve with our work in Breathe London to enable better characterization of the central tendency and hotspot identification.

While the analyses appears complex, cities can tackle them by working with the relevant experts and skilled technicians. EDF and others are increasingly making the algorithms and software necessary to make the work open-source and readily available. Algorithms used in our Houston and London work can be found at the following Github repositories.

Beyond mapping air pollution patterns and identifying hotspots, we are exploring new ways to link hyperlocal data to a deeper understanding of emission sources and health effects that will allow individuals and policy makers to take additional actions to reduce adverse impacts.

We are developing methods to quantify and map the health risks and impacts of air pollution at a hyperlocal scale.

Sensor technology is making the variation in air pollution in cities visible. But populations and health risks are not uniformly distributed across urban areas. The risks and impacts of air pollution may not follow the same pattern as that of air pollutant concentrations alone, as factors like demographics and health status that impact sensitivity to air pollution also vary across cities.

By combining information on hyperlocal air pollution with knowledge of the impact that these pollutants have on health, population distribution, and variation in risk and disease susceptibility within a city, we can quantify and map the risks and impacts of air pollution within and across neighborhoods.

Going forward, we will incorporate information on source characterizations to develop estimates of contributions of different sources to the air pollution risks and impacts in communities. Decision makers can use this health impact analysis to better understand the places and populations most impacted to effectively target mitigation action. This will be ready in 2020.

CASE STUDY: DISTRIBUTION OF NO_2 POLLUTION AND ASSOCIATED MORTALITY RISKS AND IMPACTS IN NEIGHBORHOODS IN OAKLAND, CA

EDF has intensively measured and mapped air pollution in West and downtown Oakland. Nitrogen dioxide (NO_2), a traffic related pollutant, is known to cause several adverse health effects and increases the risk of premature death.

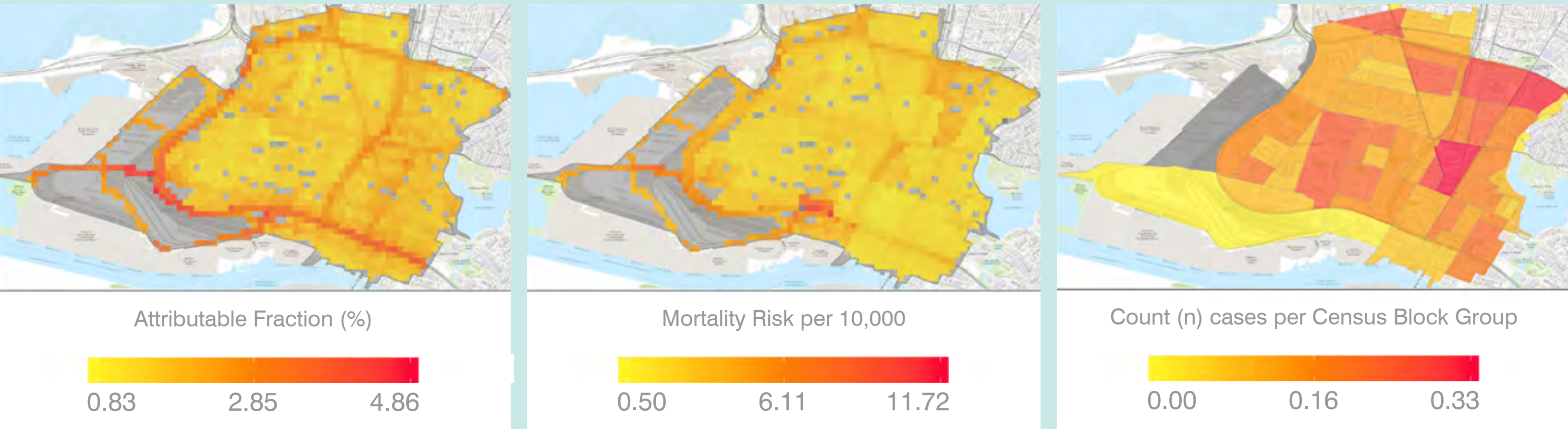
Preliminary results from our health impact study in this community indicate that NO_2 contributes to nearly 1 in 20 premature deaths (attributable fraction: 4.86%) in the areas with highest pollutant concentrations in comparison to <1 in 100 deaths (attributable fraction: 0.83%) in the areas with the lowest concentrations. However, baseline mortality rates vary from place to place due to other factors (such as poverty, race, nutrition, and health).

Using Alameda County Public Health Department mortality rates, at the census block group scale, we found that the distribution of the impact of NO_2, in terms of attributable *excess mortality risk*, was different than the pattern seen for pollutants alone, and disparities in risk were remarkable. The area with the most elevated risk (11.7 deaths per 10000 people), near the intersection of freeway I880 and I980, had twenty times higher risk than the lowest risk area (0.5 deaths per 10000 people). This is displayed below in Panel B.

Finally, incorporating the population and age data, and aggregating the results to census block group level, we were able to identify where the greatest adult (>25 yrs old) mortality impacts of NO_2 air pollution are experienced (Panel C.). This methodology reflects cumulative risks of air pollution on vulnerable populations. Without incorporating information on baseline mortality risks and population distribution, decision makers may miss important areas of at risk populations as well as the most impacted areas, where return on investments for mitigation of air pollution may be highest.

WEST OAKLAND: NO_2 ATTRBUTABLE PREMATURE MORTALITY

Geographic area: 15 km^2



A. Fraction of premature deaths attributable to NO_2 exposure

B. Excess mortality risk attributable to NO_2 exposure

C. Premature deaths per year attributable to NO_2 exposure

UNDERSTANDING SOURCE ATTRIBUTION

We are developing and testing methods that can be used to identify sources of measured air pollution using innovative, hyperlocal techniques. Our partners will use weather models to generate "footprints" describing the most likely path the air traveled on its way to being measured by the instruments. Local sources that contribute to elevated pollution levels are most likely located within these footprints. Because of uncertainties in wind speed, wind direction, and wind- and heat-driven atmospheric turbulence or mixing, these footprints resemble pieces of pie, expanding in width (and therefore uncertainty) as we move backwards in time from the measurement.

However, with many data points, measured in many locations on days with different weather patterns, we can narrow down modeled relationships between measured pollution and likely sources by overlaying these footprints to identify repeating patterns. In addition, we are also leading work to understand how improvements in meteorological models could make footprints more narrow, and possibly reduce the number of measurements needed to identify sources. We anticipate this analysis will be completed by mid-2020.

PART 03: DATA TO ACTION

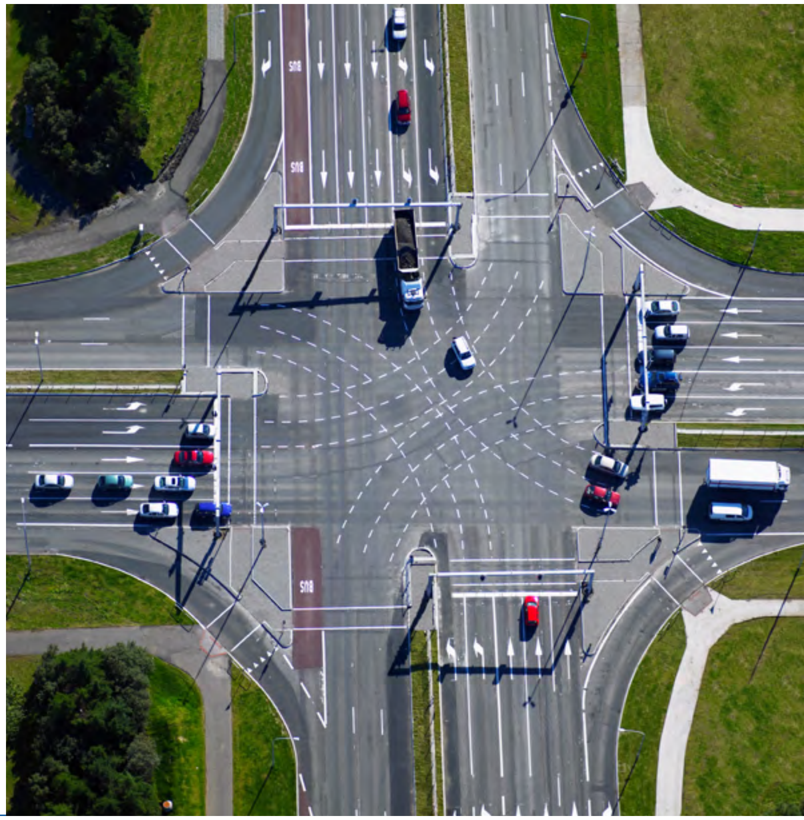
Using air pollution data to develop and implement clean air solutions

Once your team knows that the data is thorough and accurate, and once you visualize and interpret the results, you can present the facts and make the case for new policies. At their best, maps can stimulate engagement and direct people towards action. At their worst, content without context runs a real risk of numbing people to yet another threat they feel they can't do anything about. Anyone releasing hyperlocal maps should have a plan for continuing the conversation after the maps are released to explain the results and respond to questions from community members who want to use the data to enable decisions around possible steps to reduce pollution. This resource highlights many ways citizen scientists are using air pollution data to inform advocacy.

Once you've put a monitoring network in place and have ensured a reliable flow of quality data, remember that managing risk and working closely with stakeholders to outline policy changes involves many personalities and can take time. Impactful pollution reduction policies can take years to implement, long after you create your monitoring network and start working with communities. Therefore, securing funding and staffing that will sustain you for several years is necessary to maintain momentum toward significantly reducing air pollution.

The power of hyperlocal mapping will be felt in your community when a policy or action draws on the data you gathered. This can occur along many paths, each outlined below, and mapped to the possible policies and actions we listed in Part 1. Data can also support long-term changes in how your city works, and we'll close our guide with a tour through some of those changes.

- Investigation and enforcement against factories or other stationary pollution sources
- Emergency public health interventions, like evacuations, shelter in place, or public information campaigns
- Transportation planning (long-term)
- Traffic management (short-term)
- Zoning, permitting, building codes, and land use
- Targeting investments and incentives for emissions-reduction projects, like EV buses or building retrofits



Air quality dashboard

Many local leaders are already investigating and enforcing based on their existing authority, but believe they could be more efficient and effective. In Houston, we worked with Rice University to develop a dashboard so the city can target investigations better using data collected by municipal vehicles driving their regular routes. Click here for a case study on Houston's investigation dashboard.

Emergency public health interventions

If you want to coordinate work among public health officials after a natural disaster, review how we helped Houston identify elevated levels of benzene after Hurricane Harvey with this case study. As a result, our team is working with Rice University and the City of Houston to build an online platform that will alert city officials of dangerous pollution levels early, before they become a public health concern.

TRANSPORTATION PLANNING AND TRAFFIC MANAGEMENT

Many people around the world increasingly consider a personal vehicle a hassle rather than an entitlement. They are willing to consider mobility as a service, rather than an asset. Investors bet $40b in venture capital between 2016 and 2018 on this shift. China has over 400,000 electric buses on the road. Columbus, Ohio won a $50 million grant to offer to other cities its lessons in "detoxifying" transportation. Although emissions from transportation continue to grow, this too is changing. This shift is partly driven by city-led policies. Commercial vehicles in Europe will soon have to contend with zero-emissions urban access zones. Cities around the world are adopting C40 Cities' "fossil-fuel free street" goal. It aims to have cities procure zero-emission cars and remove polluting ones within a strategy of "people-friendly planning."

Data-driven methods already exist for traffic and transportation planning:

- Google's Environmental Insights Explorer combines inputs from Google maps with a tool called CURB to help estimate total tons of carbon produced per year in your city's building and transportation emissions.
- The Joaquin Decision Support Tool, which grew from an initiative in the European Community, helps decision makers and staff choose the best-fit measures to improve local air quality traffic policies. The tool organizes mitigation measures into several categories and scores each one based on a mix of literature reviews, case studies, and other inputs.

With these tools, you are able to explore improvements to baseline estimates by changing variables like total miles traveled by auto, bus, bike, foot, rail, subway, average vehicle efficiency, and emissions per type of vehicle.

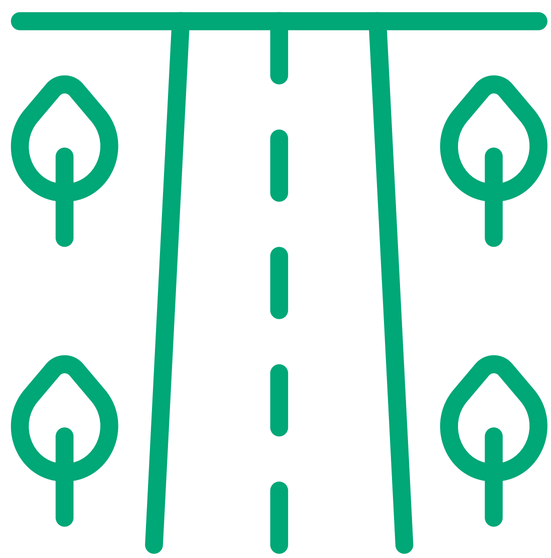
These tools, and peer-reviewed health studies and guidelines, while founded in sound science, lack the hyperlocal data clean air advocates often need to advance new policies in their cities. Hyperlocal insights offer the opportunity to pinpoint the risks and dangers of pollution where people live, work, and play. This gives advocates a rallying point to build a base of support, and gives policymakers the ability to develop targeted traffic and transportation interventions to maximize the benefits and minimize the cost of action. For example, this case study shows how community advocates used hyperlocal data from our project in Oakland to influence local traffic planning decision.

ZONING, PERMITTING, BUILDING CODES, AND LAND USE

By spotlighting both immediate and long-term perils from pollution, city governments can build a case for changes in land use or zoning. Some innovations in recent years include:

- **Pedestrian zones or car-free zones.** With these, officials designate areas of a city or town for people on foot or on bikes, and may ban all vehicles. Some experts contend these policies guide transportation officials away from prioritizing traffic and toward celebrating people. Other advocates seek similar shifts by urging cities to end free parking.
- **Clean construction requirements.** Hyperlocal data that shows hotspots or elevations at particular times can bolster support for clean construction initiatives. This approach, which has driven legislation in Pittsburgh, involves requiring low emissions and mitigation equipment on all new construction projects.
- **Zoning and permitting in environmental justice communities.** Low-income communities and communities of color experience a disproportionate burden from land use patterns and the associated impacts of polluting industries. With hyperlocal data, you can design long-term changes that can improve the imbalance. This national scan compiles 40 policies from more than 20 cities across the U.S. It includes six types of policies, from bans on certain kinds of polluting facilities to new environmental review processes to proactive planning and new health codes.

All of these policies could be more attractive, and more effective, when targeted with hyperlocal air insights.



TARGET INVESTMENTS AND INCENTIVES

As public authorities explore the value of hyperlocal air pollution data, they can work with communities to use the data to steer funds toward efforts to improve air quality. For example, AB617 in California welcomes highly granular air pollution data. Legislators drafted the bill to direct air agencies to consider localized data when investing in community air pollution mitigation efforts. With leaders paying smarter attention to environmental concerns around the world, hyperlocal air insights could increase the efficacy of public investments by ensuring the funds go to neighborhoods with the greatest air pollution burden.

Investment programs that could create greater impact by using hyperlocal air pollution insights include:

- **Vehicle replacement funds**: In the U.S., Diesel Emissions Reduction Act funds and Volkswagen Settlement funds currently help pay for transportation improvements. Cities could provide data to assist in project selection.
- **City-owned assets:** Cities are owners and managers of vehicle fleets and buildings. Investments in improvements such as EVs can be targeted to air pollution hotspots first.
- **Private assets**: The private sector is constantly investing in new vehicles, building stock, and other potential sources of pollution. Many private sector leaders have committed to climate goals, but have yet to create implementation plans. Cities could provide data and a convening pressure to encourage the private sector to target climate-driven investments to provide the greatest two-for-one health and climate benefits.
- **Building incentives:** These can include incentives to replace wood stoves or furnaces, and energy retrofit or energy efficiency funds in cities or across broader areas.
- **Green banks** and public-private impact funds: Investors and investment advisors can use hyperlocal data to prioritize projects in air-stressed neighborhoods.
- **Energy efficiency** for industrial combustion: The World Bank manages loan pools for cleaner factories or other potential polluters. Cities can provide hyperlocal information to prioritize certain areas.
- **Tax rebates and faster depreciation:** These can be directed to monitors and related equipment.

As public authorities explore the value of hyperlocal air pollution data, they can work with communities to use the data to steer funds toward efforts to improve air quality.

Building awareness and encouraging community engagement and support

Establishing an air pollution monitoring network can be a first step to characterizing or identifying air pollution problems in your city. Setting the long-term goals we outlined in Part 1.1 can transform problems into opportunities. To sustain your city's commitment to reducing pollution, you need to keep a sense of urgency. Consider these scenarios for applying the data you gathered and the collaborations you built. Tactics for creating and preserving a sense of urgency vary across conditions. In some, people know the situation is dire and requires immediate attention — they just need the data to support policy action. In others, air pollution hasn't yet registered with most people as a critical problem, therefore quantifying the pollution problem or providing proof can inspire your city to generate long-term capital for new infrastructure and projects.

Where people know that they need to reduce air pollution

In some cities, pollution is already a primary concern, with many well-established grassroots organizations already working to improve air quality. If that is the case in your area, working alongside existing community groups from the time you design your air pollution monitoring network until you are ready to communicate about your results will be essential to long-term success.

COMMUNITY ENGAGEMENT

Through our work in West Oakland, EDF learned firsthand about the importance of robust engagement with community leaders and residents - who are directly impacted by dirty air - when creating thoughtful, responsive, and impactful clean air solutions. This case study discusses strategies for effective partnership with a community group and the approaches for communicating and leveraging high-resolution air pollution data to inform mitigation actions by community members.

There are also many existing resources that provide guidance for how to conduct community- or citizen-led air monitoring, as well as how to effectively engage community members. This guide is not meant to be an exhaustive primer for community engagement best practices and we recommend reviewing the following guides before designing an air pollution network:

- California Air Resources Board Community Air Protection Program Resource Center and Blueprint
- Guidebook for Developing a Community Air Monitoring Network by the Imperial County Community Air Monitoring Project
- Citizen Science Toolkit
- THE Impact Project: Making a Case for Change

Residents and business owners may serve as willing participants in your projects, if you solicit their advice in the earliest stages. Likewise, it is important that you share your results with them — in tandem with established community groups — prior to communicating about them to the community at large. This will cement a greater sense of trust and assist in driving action.

When air pollution is less of a priority issue

However, in some cities, the threat of air pollution is not as much of a priority. In those cases, educating residents about air pollution risk is essential to making the topic personally relevant while also managing the potential stress, sense of powerlessness, or lack of control that may come with knowledge of environmental contamination. Cities are well-placed to play a leadership role in generating awareness and organizing stakeholders to take action to address the problem of air pollution.

To get this process started, a strategy you can adopt early in the engagement is mapping the assets of your city. Asset maps are commonly used to conceptualize resources in a community, such as the capabilities of local talent, the reach of community-based organizations and academic institutions, as well as sources of financial assistance and technical support. From this early assessment you will have an idea of what local organizations exist that may have the bandwidth to tackle difficult environmental problems, and you can assess the value of forming long-term partnerships with these organizations.

Establishing long-term partnerships with community-based organizations is also critical for your city in order to develop trust and build awareness in communities. Working closely with community-based organization is essential to help surmount a common lack of trust in government bodies, much of which has its roots in systemic injustices. Most community-based organizations are culturally competent and have diverse staff which helps develop rapport in frontline communities; they also often have served communities for decades and centuries at a time, which helps establish intimate connections on the ground. As part of relationship and trust building process, you may consider drafting a partnership agreement — based on sound community engagement principles — to define a shared vision and goals for a project, and to clarify the roles of each organization.

EDF's involvement with One Breath Partnership is one example of a collaborative initiative that leverages efforts by multiple organizations in the Houston area to amplify the work of local scientists, researchers, academics, and physicians in order to educate community members about the impact of air quality on their health. The partnership also provides an outlet for residents to share their own stories about the harmful effects of air pollution and advocate for solutions.

Since early 2017, the partnership has been the catalyst for more than 5,500 news stories on Houston's air quality, or roughly seven news stories a day. The increased media attention has put pressure on government at all levels to act. For example, Texas and Harris County agencies are seeking additional funding for air quality monitoring equipment and personnel, while the Attorney General's Office is stepping up enforcement actions against corporate polluters.

You have an opportunity to educate residents in several forms, from data visualization workshops to media campaigns and advertisements. Citizen science, or the public's direct participation in collecting, analyzing, and interpreting scientific data, has also proven effective in translating results to action and prompting local clean air solutions. Several case studies founded on community engagement principles have successfully moved from data collection to enforcement of policies and solutions that address air pollution. These and others feel less technical than guidance on designing or operating monitors, but provide examples to spur your thinking.

Communicating your results

To create a communications plan that showcases your results, you should first ask a series of critical questions:

1. Who is the audience for these results and what do I want them to do?
2. What kinds of messaging and communications will motivate them?
3. Which channels are most effective at reaching my target audience?
4. When and at what stage should I communicate about this work?
5. How will I determine success?

You can assume a range of audiences for your marketing and communications plan — and each may be motivated by different messages. In some cases, you will need to ensure your messages are broad-reaching and inclusive of all audiences, which may require, for instance, pitching international news outlets and communicating in multiple languages. In other cases, you will need to tailor messages to specific audiences. In this case, scientific results from air pollution measurements can be dense and, at times, difficult to understand for individuals who do not have technical backgrounds. We have found that for most air pollution monitoring efforts, key audiences include:

- Community members (individuals)
- Community-based organizations
- Local and state/territorial elected officials
- Local air quality regulators/monitors
- State/Territory/National air quality regulators
- Air pollution researchers
- Air pollution technologists
- Funders

The top of this list represents the least specialized audience — though a very critical one. Community members hold extremely valuable local knowledge, are directly impacted by air pollution and, therefore, have a right to know what's in the air they are breathing. Winning their support will require you to both communicate your findings clearly and demonstrate why they should spend time supporting a monitoring project. Likewise, for each of the subsequent groups, understanding what could motivate them to support you, work with you, or create/change policies will require a keen understanding of their self-interests and needs. With that information in hand, you can begin to develop your messaging.

Developing salient messages for your audiences

Once you map your various audiences and the actions you wish them to take, as well as what could motivate them to do so, you can create messaging material. Many organizations create a series of overarching messages — those that are general enough to meet everyone. These tend to include a series of main ideas and supporting statements that back up those ideas with facts and statistics. For example, here is a link to the Breathe London talking points.

To be successful at motivating individual audiences to support your efforts, however, you should also consider creating series of messages that will be both of interest — given their area of expertise — and motivating. For example, you may wish to utilize information on the health benefits from reducing air pollution to motivate elected officials, while using information about the growing market for air sensor technology for business leaders.

Because visualizing pollution is such a critical part of these efforts, it's also important to develop and distribute images, interactive maps, and graphics that will speak to a variety of audiences. You should consider developing a series of visuals that will speak both to your lay audiences as well as technical experts.

Identifying and activating channels

To deploy your messages to specific audiences, it's important to understand where people get their information. Your local press no longer carries authority for everyone: instead, different media reach different audiences in different ways. It's often useful to think of them in the following four categories:

- **Paid:** This includes traditional advertising in print and television media, online, as well as native ads, sponsored content on media sites and on the social web, and paid sponsorships at conferences.
- **Earned:** Traditional media organizations (TV, newspapers, magazines, online outlets, trade publications and television, radio, and social influencers who may share your story), or possibly conferences where you are presenting.
- **Shared:** Partner websites and blogs, social media platforms, and events.
- **Owned:** Your organization's website and blogs, newsletters, visuals, direct emails/meetings with stakeholders, news releases, and social platforms.

Many organizations find it useful to develop maps that show how they will use specific channels and messages to meet their priority audiences. This can help identify gaps as well as opportunities.

Timing your communications

You may find there are multiple opportunities to communicate about your efforts, including:

- Deployment of the sensor network/mobile monitors
- Technical milestones
- When initial results are available
- When air quality is in the news and provides you an opportunity to comment
- When peer-reviewed scientific papers are published
- When action is taken as a result of your efforts

These are not the only opportunities to communicate about your efforts — just some of them. And you will find that each instance prompts a different type of communication. Working alongside your partners will ensure a more coordinated approach and allow you to amplify the others' efforts.

Setting up your communications plan for success

Prior to the development of your communications campaign, as with your monitoring program, it's important to ask the question, "To what end?" Are you hoping to achieve a policy goal? Are you looking to expand your monitoring effort to additional locations? Are you hoping to attract additional funding and partners? Your communications efforts should align with your strategic goals, which should serve as your north star. Reminding your organization of what it hopes to achieve through its monitoring and communications campaigns will help streamline your efforts so you can use your resources effectively and reduce unnecessary activities.

Measuring success and maintaining momentum

How do you produce continuous improvements in air pollution reductions, perform ongoing health impact assessments, and sustain a network of well-running monitors? Government ownership of air quality goals is a key component of maintaining momentum. Considering that air quality concerns are spread throughout several departments within a city, such as Urban Planning, Sustainability, Energy, Transportation, and Public Health, fostering collaboration across agencies is essential to leverage resources and build on existing programs and budgets.

To motivate collaboration across departments over time, consider emphasizing how air quality can define your city's prospects. Show how it affects everything from healthcare costs to labor and productivity losses, as well as the consequences for travel and tourism industries. If asthma is one of the leading causes of school absenteeism, school performance and children's health may move your city toward air pollution investments. The Health Impact Assessment analysis outlined in Part 2.3 may be useful to show impacts before and after an intervention. These factors and others can help gain financial backing for monitoring and mitigation in your city and transform technical arguments into commitments with far-reaching benefits.

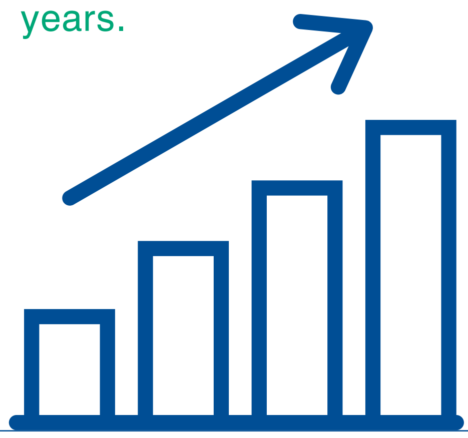
The enactment of policies to improve air pollution may transpire several years after your monitoring network is established and the initial engagement with the community has ensued. To this point, mechanisms must be in place to sustain momentum which is largely dictated by funding streams and the level of resources. One critical step for cities to captivate funders is by highlighting interlinkages between air pollution and other daunting threats, like climate change. For example, several air pollutants are chemical precursors for greenhouse gases; nitrogen oxides and volatile organic compounds emitted from power plants and other industrial sources react with sunlight to form ozone, a main contributor to radiative forcing. Rising temperatures also spur building occupants to crank air conditioners, which can inadvertently boost particulate matter levels. Therefore, government weatherization programs and energy efficiency schemes can lead to avoided or indirect emission reductions and should be promoted in your city to both counter climate change impacts and concurrently improve air quality.

To monitor progress over time, you should document successes toward an air quality goal with your core team at least once a year. Other cities are actively using computer-based surveys to track similar trends. For example, the Ohio Moves Transportation Study and Make Your Trip Count Commuters Survey both monitor trends in mobility to help forecast travel needs in the future. As mentioned previously, the United Nations and the World Bank have created a standard for air pollution and GHG reporting. The detailed protocol is available online as are online training courses which provide support for developing an inventory. These kinds of tools and others can help your city coordinate policies for lowering pollution that resonate in people's minds.

Measures of success will come with time as you benchmark progress over consecutive years. They will come in dialogue with local experts who deal with climate, urban metabolism, and energy planning. They will also arise from quarterly C40 Cities webinars, which will allow cities to showcase step-by-step, successful case studies and ongoing work. By tracking and reporting air pollution in your city, more data is available to accurately calculate reductions.

This guide will update and improve as science focuses and data define steps to cleaner air. Your use of it will gain clarity as you connect it to an incompletable question: what art, companies, breakthroughs, and memories will people create in your city when nobody has to breathe toxic air? Who can you listen to, teach, learn from, and motivate to bring those breakthroughs forward? Continuous new data, readable at the block level, can lead to new partnerships that reinforce your efforts toward governing a city with healthier air and healthier residents.

Measures of success will come with time as you benchmark progress over consecutive years.



LIST OF EDF RESOURCES

PART 01: GETTING STARTED

- Emergency response monitoring case study
- Community engagement and data-to-action case study

PART 02: NUTS & BOLTS

- Future Fleets report
- Cost of hyperlocal mapping tool
- Air Quality Data Commons
- Documents related to setting up monitoring systems
    - 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
    - Houston low-cost mobile final report
    - Project proponent and city low-cost mobile partnership and bailment agreement
    - Project proponent and consultant low-cost mobile service and bailment agreement
    - Stationary sensor network host agreement form
- Standard operating procedure documents related to day-to-day operations
    - Low-cost mobile instrument O&M SOP
    - Breathe London mobile monitoring instrument O&M SOP
- Examples of data visualization tools
    - Breathe London air quality map
    - 100x100 West Oakland community black carbon sensor network data portal
- Data processing algorithms for London mobile monitoring data

PART 03: DATA TO ACTION

- Air quality dashboard overview
- Emergency response monitoring case study
- Community engagement and data-to-action case study
- One Breath Partnership
- Breathe London talking points

LIST OF PARTNERS IN AIR MONITORING PROJECTS DISCUSSED IN THIS GUIDE

ACLIMA

AIR MONITORS

BAY AREA AIR QUALITY MANAGEMENT DISTRICT

C40 CITIES

CAMBRIDGE ENVIRONMENTAL RESEARCH CONSULTANTS

CITY OF HOUSTON

GOOGLE EARTH OUTREACH

KING'S COLLEGE LONDON

MAYOR OF LONDON

NATIONAL PHYSICAL LABORATORY

RICE UNIVERSITY

TD ENVIRONMENTAL

THE UNIVERSITY OF TEXAS AT AUSTIN

UC BERKELEY AND LAWRENCE BERKELEY NATIONAL LAB

UNIVERSITY OF CAMBRIDGE

WEST OAKLAND ENVIRONMENTAL INDICATORS PROJECT

Endnotes

1 Brook RD, Rajagopalan S, Pope CA, et al. Particulate Matter Air Pollution and Cardiovascular Disease. An Update to the Scientific Statement From the American Heart Association. 2010;121(21):2331-2378.

2 Brook RD, Franklin B, Cascio W, et al. Air Pollution and Cardiovascular Disease. A Statement for Healthcare Professionals From the Expert Panel on Population and Prevention Science of the American Heart Association. 2004;109(21):2655-2671.

3 Zirogiannis N, Hollingsworth AJ, Konisky DM. Understanding Excess Emissions from Industrial Facilities: Evidence from Texas. Environmental Science & Technology. 2018;52(5):2482-2490.

4 Primary pollutants are emitted directly by a source. Secondary pollutants are formed as a product of chemical reactions in the air and are more mixed and diffused. Primary pollutants tend to be more localized and easier to associate with a source than secondary pollutants.

5 For the purposes of this guide, "mobile" monitoring refers to measurements being taken while the vehicle is on the move (as has been the case in our mobile monitoring campaigns employing Google Street View vehicles or municipal fleet that drive continuously). This differs from "movable" monitoring, where monitors are on a mobile platform which can be moved to a location but take measurements while stationary. This type of monitoring is sometimes referred to as "short-term stationary."

6 Reproduced from Caubel JJ, Cados TE, Preble CV, Kirchstetter TW. A Distributed Network of 100 Black Carbon Sensors for 100 Days of Air Quality Monitoring in West Oakland, California. Environmental Science & Technology. 2019;53(13):7564-7573.

7 Apte JS, Messier KP, Gani S, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environmental Science & Technology. 2017;51(12):6999-7008.

8 Accuracy describes the degree of closeness of sensor concentration measurements to the actual (true) concentration value. Precision is the ability of a sensor or instrument to measure the same concentration in a consistent manner. Bias is any systematic error in reporting a measurement value that deviates from the true value. For more details consult: https://www.epa.gov/air-sensor-toolbox/how-use-air-sensors-air-sensor-guidebook.

9 Details of 100x100 network data processing and analysis can be found in: Caubel JJ, Cados TE, Preble CV, Kirchstetter TW. A Distributed Network of 100 Black Carbon Sensors for 100 Days of Air Quality Monitoring in West Oakland, California. Environmental Science & Technology. 2019;53(13):7564-7573.

10 Data visualization tool developed by Distributed Sensing Technologies, LLC.

11 For examples, see the following papers. Note that this is not meant to be an exhaustive review of the literature on analysis of hyperlocal air pollution datasets.

Choi W, Hub S, He M, et al. Neighborhood-scale Air Quality Impacts of Emissions from Motor Vehicles and Aircraft. Atmospheric Environment. 2013;80:310-321.

Van den Bossche J, Peters J, Verwaeren J, et al. Mobile Monitoring for Mapping Spatial Variation in Urban Air Quality: Development and Validation of a Methodology Based on an Extensive Dataset. Atmospheric Environment. 2015;105:148-161.

Heimann I, Bright VB, McLeod MW, et al. Source Attribution of Air Pollution by Spatial Scale Separation Using High Spatial Density Networks of Low Cost Air Quality Sensors. Atmospheric Environment. 2015;113:10-19.

Ranasinghe DR, Choi W, Winer AM, Paulson SE. Developing High Spatial Resolution Concentration Maps Using Mobile Air Quality Measurements. Aerosol and Air Quality Research. 2016;16(8):1841–1853.

Lia HZ, Gua P, Ye Qing, et al. Spatially Dense Air Pollutant Sampling: Implications of Spatial Variability on the Representativeness of Stationary Air Pollutant Monitors. Atmospheric Environment X. 2019;2:100012.

12 Messier KP, Chambliss SE, Gani S, et al. Mapping Air Pollution With Google Street View Cars: Efficient Approaches With Mobile Monitoring and Land Use Regression. Environmental Science & Technology. 2018;52(21):12563-12572.

13 Apte JS, Messier KP, Gani S, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environmental Science & Technology. 2017;51(12):6999-7008.

14 Apte JS, Messier KP, Gani S, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environmental Science & Technology. 2017;51(12):6999-7008.