WRI BRASIL

PRACTICE NOTE

Measuring $PM_{2.5}$ with Low-Cost Sensors

Practice notes provide rapid analysis of experiences related to a particular project. The analysis and recommendations are limited to the specific context presented in the note and should not be construed to apply more broadly.

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EXECUTIVE SUMMARY

HIGHLIGHTS

- In 2018, WRI evaluated the use of low-cost air quality sensors[1] measuring particulate matter 2.5 ($PM_{2.5}$) concentrations on some days of an urban intervention, São Paulo's Car-Free Friday. The use of these sensors can enhance both the existing network of air quality monitors in cities as well as analysis of the impact of specific initiatives. This project seeks to help cities by sharing methodology used, lessons learned, key takeaways, and best practices.
- São Paulo's Car-Free Friday initiative closes off streets in the historic center of the city on the last Friday of each month. WRI used low-cost air quality sensors—in both fixed and mobile modes—to measure $PM_{2.5}$ concentrations on some days of this initiative.
- Logistical preparations with a large number of measuring instruments are also provide valuable lessons learned from this project. This practice note discusses procedures to calibrate the instruments, to prepare a site to install a low-cost sensor, and to maintain and manage the instruments.
- Data generated indicate that the initiative may be having a positive impact on local $PM_{2.5}$ concentrations. Despite the small sample of days, the analysis revealed a significant statistical difference between the $PM_{2.5}$ concentrations on Car-Free Fridays and those on regular Fridays.

CONTEXT

Air pollution is the top environmental cause of disease in the world (Landrigan et al. 2018). This makes providing an air quality monitoring network increasingly important. While scientists have noted uncertainties associated with them, low-cost air quality sensors still provide valuable "policy-relevant and society-relevant information" (Gupta et al. 2018).

Currently, the air quality reference monitoring network in Brazil is poorly maintained. Acquisition, maintenance, and operation high costs of conventional monitoring stations do not allow most cities to have sufficient geographic coverage of monitoring stations spread across their airshed (ISS 2014; IEMA 2014).

Although low-cost sensors are not yet as accurate as traditional monitoring stations, they do offer several advantages: they are portable, easier to use, and more can be deployed due to their lower cost. These instruments provide an opportunity to conduct special monitoring studies and should be tested as a complementary technology to the traditional monitoring stations, helping cities to increase monitoring capacity and public awareness about air quality.

ABOUT THIS PRACTICE NOTE

The objectives of this practice note are to evaluate low-cost sensors' effectiveness, assessing methodology, lessons learned, key takeaways, and best practices for future studies with these instruments. A secondary objective is to evaluate the air quality impact of using low-cost sensors in an urban intervention (São Paulo's Car-Free Friday).

AirBeam2, which measures $PM_{2.5}$, temperature, and relative humidity, was selected as the low-cost air quality instrument. The technology used by AirBeam2 makes it possible to transmit data in real time through the AirCasting platform. It can work in fixed or mobile modes. In the fixed mode, the sensors generate data every minute. In the mobile mode, AirBeam2 collects data every second, which generates a map of air pollution. Both fixed and mobile modes are used in this project. Car-Free Friday (CFF), an initiative that closes off streets in the historic center for all private cars and motorcycles on the last Friday of each month, was chosen as the scenario for the pilot project application with low-cost sensors.

Several logistical procedures were undertaken to ensure and control the quality of the measurement study. A total of 30 sensors were deployed for this project, with 21 used in the field study. Some of the nonselected sensors were set aside because of operational difficulties and others due to lower correlation identified in the initial collocation.

METHODOLOGY AND RESULTS

The methodology of this project can be divided into three major components:

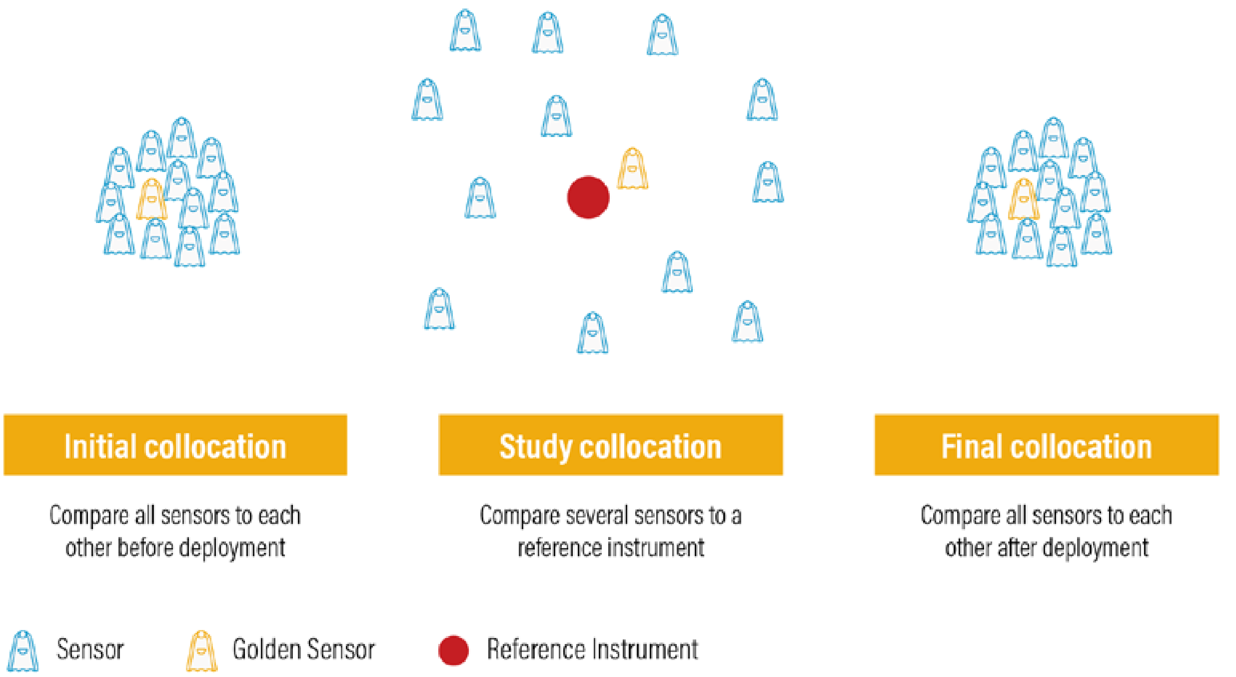
- Collocation
- Fixed sensor study
- Mobile sensor study

Collocation is the process of comparing data collected from a sensor, whose performance is unknown or not well understood, with data collected by a reference instrument, whose performance is well established and trusted as a result of prior evaluation. Traditional monitoring stations can be used as reference instruments to evaluate the quality and accuracy of low-cost sensors. In São Paulo, monitoring stations are managed by the Environmental Company of the State of São Paulo (CETESB). In this study, one of CETESB's reference-grade monitoring stations (in Dom Pedro II Park) was used to evaluate the performance of the low-cost air quality instruments deployed.

Data must be adjusted using regression equations generated from the collocation. During the study, a continuous collocation was performed with a sensor (called the golden sensor) located next to a reference monitoring station, as shown in Figure ES-1. The assessment with the monitoring station confirmed the reliability of the low-cost sensors, but it wasn't used as an adjustment equation to relate other sensors to the reference instrument data. To guarantee the high quality of data collected and to adjust the measurements from the low-cost instruments, a collocation of all sensors was performed before and after the field measurements.

After the initial collocation, 13 sensors were deployed for a **fixed sensor study** (i.e., sensors were installed in a fixed location for measuring $PM_{2.5}$ concentrations), 11 outside public buildings in the central part of the city and 2 near the reference instrument. The 13 fixed sensors were divided between two zones (the Car-Free Zone [CFZ] and the Non-Car-Free Zone [NCFZ]) to

Figure ES-1 | Collocation Phases



Source: Authors.

evaluate the impacts of the Car-Free Friday initiative. These sensors measured PM concentrations every day from September 28 to November 22, 2018 (September 26 to November 23 considering collocations).

The hourly average $PM_{2.5}$ concentration was calculated for each zone and a comparison was made between the measurements from the CFZ and the NCFZ. For each day, statistical tests were performed to check for percentage differences between zones, using the difference-in-differences method. Then paired t-tests were used to compare mean differences among days. Data from all Fridays measured during the study period (except holidays) were compared.

In addition to the fixed study, five sensors were deployed for a **mobile sensor study** (i.e., sensors connected to a smartphone). Study participants carried a mobile sensor and walked along different routes. Mobile $PM_{2.5}$ measurements occurred on two Car-Free Fridays (September 28 and October 26) and on three regular Fridays (October 5, October 19, and November 9) at three different times (9 a.m. to 10 a.m., 12:30 p.m. to 1:30 p.m., and 4 p.m. to 5 p.m.). The remaining sensors that were not used in both studies served as backup sensors for the study.

The **collocation** has shown that the measurements from the low-cost air quality sensors were well correlated with one another ($R^2 > 0.94$). When compared to the reference instrument, they also obtained a reasonable coefficient of determination (R^2), with an R^2 for hourly means of approximately 0.68, while for the daily means the R^2 was approximately 0.9. When combined with other information, the sensors demonstrated that they could give good indications of PM concentrations.

For the **fixed sensor study**, measurements have shown that, on all Fridays, the $PM_{2.5}$ concentration inside the CFZ was slightly higher than in the NCFZ. On Car-Free Fridays, the difference between the zones was smaller than on other Fridays. The results show a significant difference between Car-Free Fridays (CFFs) and Non-Car-Free Fridays (NCFFs) in all cases (each day compared to another), when eliminating outliers. These results suggest that the Car-Free Friday initiative may have an impact on $PM_{2.5}$ concentration in that area. However, since the measurements were only taken on two Car-Free Fridays, more studies need to be done to statistically validate these results.

For the **mobile sensor study**, data on five Fridays were collected, using five sensors on each of these days. This generated an abundance of data, which serves to verify the potential of data visualization insights for projects with low-cost sensors. Despite the limited number of days analyzed, having such visual analysis can show some interesting features (e.g., hotspots) worth further investigation and might help to better identify sources of pollution in different areas.

LESSONS LEARNED

This project demonstrates several lessons learned that are worth sharing for future deployments of low-cost sensors. Logistical issues and data analysis challenges when dealing with large numbers of sensors, the importance of collocation with a reference instrument to analyze the study's accuracy, and the need to engage with city officials in implementing the project are some points highlighted.

INTRODUCTION

Air pollution is the world's top environmental cause of disease. In 2015, diseases caused by pollution were responsible for an estimated 9 million premature deaths (Landrigan et al. 2018). According to the World Health Organization (WHO), more than 90 percent of the world's population lives in areas with unsafe air quality levels, the majority of these people in developing countries (WHO 2016). This is a symptom of a larger development challenge, combined with a slow energy transition, a lack of political will, and governance structures that can be difficult to navigate. But awareness of the risks of air pollution is growing (WHO 2016), and the proliferation of low-cost sensors can help to increase it. While uncertainties have been raised by atmospheric scientists who question the performance, accuracy, and reliability of low-cost air quality sensors, these instruments still provide valuable "policy-relevant and society-relevant information" (Gupta et al. 2018). In 2018, the World Meteorological Organization (WMO) released a comprehensive report recommending situations in which low-cost air quality instruments should be used. The WMO concluded that low-cost sensors are not yet a substitute for reference instruments but can be a useful complementary source of air quality information (WMO 2018).

In its current state, the air quality reference monitoring network in Brazil is costly to properly operate and maintain. Management of air quality is a state-level responsibility, but most Brazilian states do not have monitoring stations (ISS 2014; IEMA 2014). Due to the high up-front costs of acquisition, and of the maintenance and operation of conventional monitoring stations, most cities do not have sufficient geographic coverage of monitoring stations spread across their airshed (ISS 2014; IEMA 2014). With no reference network, it is difficult to apply special monitoring projects. While low-cost sensors are not yet accurate enough to replace reference-grade air quality instruments, they can be used to supplement the network in locations with fewer resources. These sensors provide an opportunity to conduct special monitoring studies. New low-cost sensors should be tested as a complementary technology to the traditional monitoring stations, with the aim of increasing cities' monitoring and management capacity—in addition to increasing public awareness.

The current use of low-cost sensors to measure air quality in cities is still experimental (Karagulian et al. 2019). Although low-cost sensors are not yet as accurate as traditional monitoring stations, they offer several advantages: they are portable, easier to use, and more can be deployed due to their lower cost. Gupta et al. (2018) used low-cost sensors and satellite observations to generate statistical models, obtaining reasonable "policy-relevant" results. Castell et al. (2017) found that low-cost sensors can be useful in providing socially relevant information on air quality.

Many low-cost air quality sensors are available on the market. Besides measuring different pollutants, each model has unique functions and characteristics, and different performance in terms of accuracy and precision. Several factors were considered in selecting sensors: cost, pollutants measured, data communication methods, and vendor support. For this study particulate matter (PM) sensors were selected. Particulate matter includes small particles suspended in air, which those with a diameter of less than 10 micrometers can penetrate, enabling them to lodge inside the lungs. Particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) is one of the most-studied pollutants and is associated with significant health risks (WHO 2016). Low-cost $PM_{2.5}$ sensors have proved to be reasonably reliable and accurate (Magi et al. 2020; Feenstra et al. 2019).

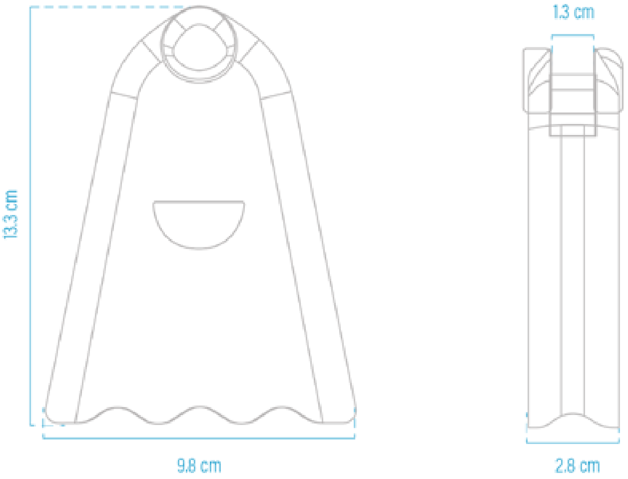
In parallel to the ground-up, citizen-science nature of low-cost air quality sensors, cities are implementing emission-reduction strategies to move from awareness to action. Many cities around the globe (Masiol et al. 2014) are taking actions to improve air quality and minimize the growing health impacts.

The objectives of this practice note are to evaluate low-cost sensors' effectiveness, highlighting the methodology used, final lessons learned, key takeaways, and best practices for future studies using low-cost sensors, with the aim of helping cities be better prepared to do their own special projects. A secondary objective is to assess the air quality impact of using low-cost sensors in an urban intervention.

AirBeam2 was selected as the low-cost air quality instrument. AirBeam2 measures $PM_{2.5}$, temperature, and relative humidity. The AirBeam2 is an updated model of the original AirBeam, which at the time of this study had already been evaluated by a reputable institution and found to perform well (AQ-SPEC 2019). The instrument dimensions are given in Figure 1. Some of the key factors driving the selection were fixed and mobile modes of operation, multiple communication methods (Wi-Fi and cellular), ease of use, power from a battery or external power source, and an online platform for real-time viewing of data.

The technology used by AirBeam2 makes it possible to transmit data in real time through the AirCasting platform. It can work in fixed or mobile modes. In the fixed mode, the sensors generate data every minute. Figure 2 shows how to view data online. In

Figure 1 | **AirBeam2 Dimensions**



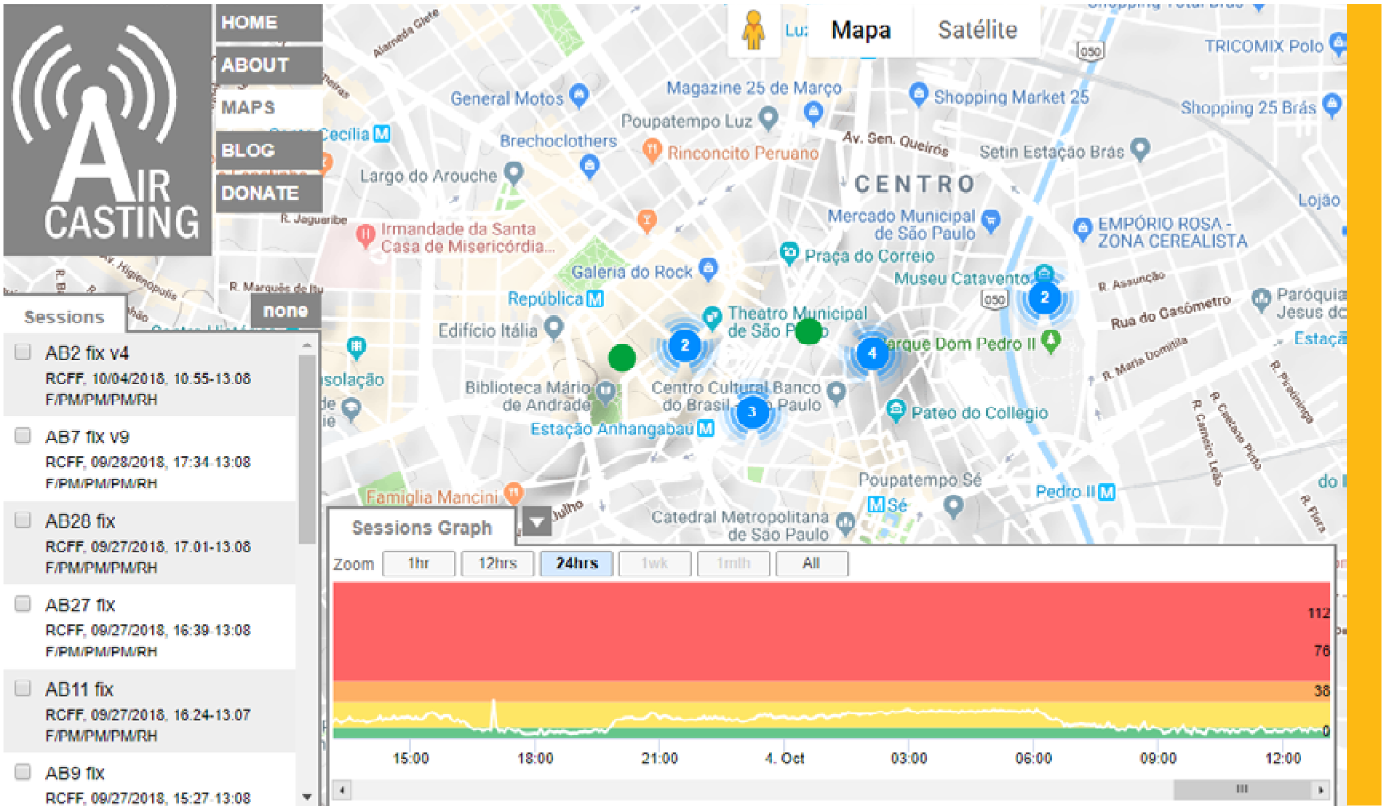
Source: Authors.

the mobile mode, the AirBeam2 must be connected to an Android smartphone via Bluetooth to properly geolocate and timestamp the measurements. In the mobile mode, AirBeam2 collects data every second, which generates a map of air pollution. Both fixed and mobile modes are used in this project.

In areas where traffic is shown to be one of the dominant sources of emissions (Karagulian et al. 2015), strategies such as low-emission zones (LEZs) and car rationing (e.g., even/odd license plate programs) are being implemented. In the case of São Paulo, one initiative undertaken by the city that began as a pilot but is now fully operational is the Car-Free Friday initiative. Car-Free Friday was chosen as the scenario for the pilot project application with low-cost sensors.

The Car-Free Friday initiative closes off streets in the historic center to all private cars and motorcycles on the last Friday of each month from 6 a.m. to 6 p.m. Buses, taxis, bicycles, school buses and

Figure 2 | **AirCasting Platform**



☐ AB2 fix v4
RCFF, 10/04/2018, 10.55-13.08
F/PM/PM/PM/RH

☐ AB7 fix v9
RCFF, 09/28/2018, 17:34-13:08
F/PM/PM/PM/RH

☐ AB20 fix
RCFF, 09/27/2018, 17.01-13.08
F/PM/PM/PM/RH

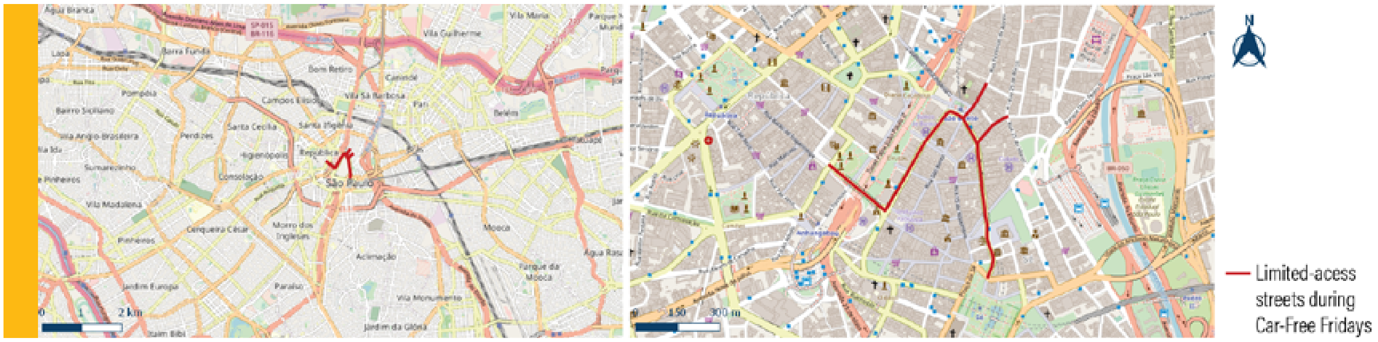
☐ AB27 fix
RCFF, 09/27/2018, 16:39-13:08
F/PM/PM/PM/RH

☐ AB11 fix
RCFF, 09/27/2018, 16.24-13.07
F/PM/PM/PM/RH

☐ AB9 fix
RCFF, 09/27/2018, 15:27-13:08

Source: aircasting.habitatmap.org.

Figure 3 | **Historic City Center of São Paulo and Car-Free Friday Roadways (Red)**



Source: Authors.

cars carrying the elderly or people with disability credentials may continue to circulate, as can drivers who are residents of the area. The streets highlighted in red in Figure 3 are those designated as “car-free” on the last Friday of each month.

Initially conceived as a pilot, São Paulo’s first Car-Free Friday took place on September 22, 2017, as a part of World Car-Free Day and Mobility Week. The popularity of the initiative with the public and the mayor led to its long-term institutionalization, and Car-Free Fridays have continued since September 2017. In October 2018, WRI surveyed more than 500 people about the Car-Free Friday initiative: 77 percent of respondents said they would like to increase the frequency of Car-Free Fridays and replicate the initiative in other areas of the city.

LOGISTICAL PROCEDURES

Several logistical procedures were undertaken to ensure and control the quality of the measurement study. The first step was to determine how many air quality sensors to use. Not having the right quantity of air quality instruments can make a measurement study much more challenging logistically. A total of 30 sensors were deployed for this project, although not all of them were used in the field studies.

INITIAL CHECKING STEPS

Upon receiving new low-cost sensors, it was important to set up each one to make sure it worked, to confirm that no damage had occurred during shipping, and to draw up an inventory list to help management. The initial steps were to:

- create an inventory list;
- inspect each sensor for visible signs of damage;
- assign a code to and label each instrument;
- charge the battery for the time recommended by the manufacturer; and
- upgrade the firmware to its latest version.

Even these relatively simple steps can take a long time when several sensors are used. For example, a simple five-minute firmware update, applied to 30 sensors, can take 2.5 hours to complete. As the number of sensors increases, such seemingly small tasks can lengthen a project’s schedule significantly.

LOGISTICS OF FIXED SENSOR SYSTEM

Siting any air quality measuring instrument can be challenging due to atmospheric conditions, local emissions, and logistical considerations, such as obtaining permission to access the site. For example, a smokestack or vent emissions could interfere with measurement of air quality conditions over a larger region like a neighborhood or city. Other factors like power and security can limit where sensors may be located. It takes time to find an appropriate site for any fixed sensor.

For this study, fixed sensors were installed on the exterior of windows of city government buildings. A partnership with the municipality helped with access. The installation of the physical sensors was quick (about one to two hours for each sensor), but getting access to the site took several weeks, requiring coordination with different actors and local visits to check whether and how the location could be used.

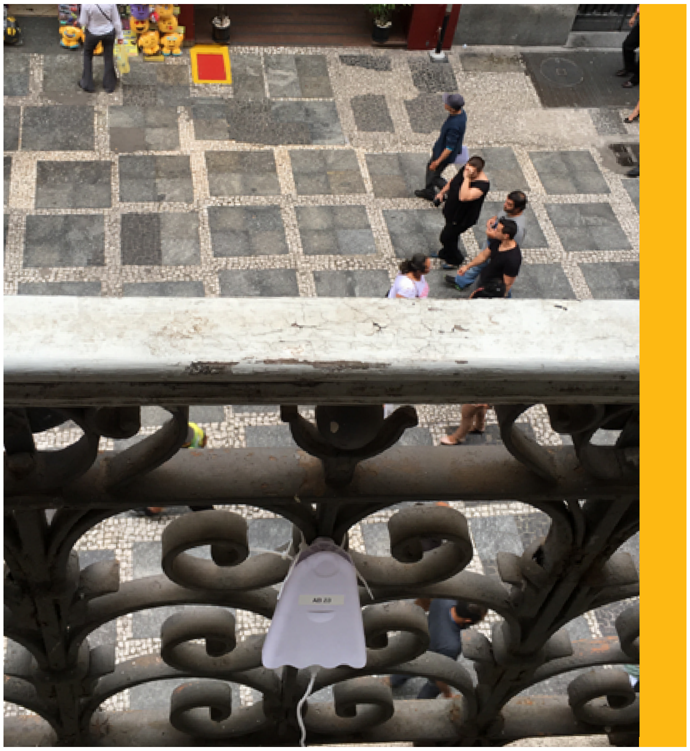
The low-cost air quality instruments were placed sufficiently far from nearby structures to prevent air flow restrictions. Sensors were placed in an outdoor location that assured air flow. The height chosen was between buildings' second and third floors. Because they were at similar heights, the instruments could be better compared. This height proved suitable for locating all the sensors and more secure than on the ground floor, where they are more vulnerable to theft. Local emissions sources may affect the data collected at a site, so nearby sources that might bias the data were checked. All the sites chosen had guaranteed access and offered safety for personnel performing installation, routine visits, and maintenance. It was also important to make sure that power sources were available next to the windows where the sensors would be placed and that city employees knew not to turn them off. Figure 4 shows an example of fixed sensor installation.

The cellular network connection was sufficient and reliable in the region, avoiding the need to utilize a Wi-Fi connection. Communication systems in the area were tested before deploying the sensors.

After the sensors were turned on and configured, they were physically installed at their outdoor locations. Installers made sure the power cable was secure and would remain fixed in normal weather conditions, such as rain and wind.

Once the sensors were installed, the network's operation was monitored online to ensure that sensors were sending data correctly. In some instances, the sensors stopped sending data. Sometimes this could be fixed by restarting the instrument; in one instance the sensor had to be replaced.

Figure 4 | **AirBeam Installed**



Source: Seth Contreras/WRI.

LOGISTICS OF MOBILE SENSOR SYSTEM

When choosing mobile routes, it is important to ensure that the objective of the data collection is being satisfied. In this case, the objective was mostly to evaluate potential use for data visualization, and measurements inside and outside the area of study were taken. The choice of routes influenced the number of people required to walk with the sensors.

To ensure correct data collection with simultaneous mobile measurements at the same times and locations, participants who walked the routes were trained. Study participants were instructed to place the sensors at waist height. It was important to standardize how to use the sensors and how to name recording sessions, to teach participants how to connect sensors with cell phones, and to provide general tips (e.g., to avoid following people smoking).

DATA MANAGEMENT

Sites were named based on geographic landmarks that could be easily identified on a map. Their names included that of the building and the address. When there was more than one sensor on the same building, they faced different streets, so the street names were used.

The $PM_{2.5}$ data collected from the low-cost sensors were sent automatically to the AirCasting.org website, where they could be plotted and displayed on a map in near real time. All data were stored on the AirCasting.org server, and systematic downloads of data were done manually to maintain a backup database.

Traditional monitoring stations provide a reference for air quality concentrations and can be used to evaluate the quality and accuracy of low-cost sensors. In the São Paulo metropolitan area, 29 monitoring stations are managed by the Environmental Company of the State of São Paulo (CETESB), 17 of which perform $PM_{2.5}$ measurements (CETESB 2019). In this study, one of CETESB's reference-grade monitoring stations (in Dom Pedro II Park) was used to evaluate the performance of the low-cost air quality instruments deployed.

Data from the CETESB reference instrument were necessary to address the study objectives of comparing the data from the low-cost instruments to the reference-instrument measurements; reference data were available on the official CETESB website. Data delivered were processed on a periodic basis and backed up.

CONTINGENCY PLANNING: SENSOR BACKUP APPROACH

Some sensors may fail, sustain damage, or be stolen; therefore, backup sensors were available as replacements. Only one AirBeam2 was replaced during the two-month study, due to operational problems. Due to the project's complexity, it was important to document this problem, to know which sensor had failed, where this sensor was located, and when it was replaced.

DATA QUALITY ASSURANCE PROCEDURES

Data validation is the process of determining the quality and validity of observations. Several procedures were needed to ensure that data were of sufficient quality for analysis. The quality assurance included developing a project plan (which guided the whole study), assessing sensors' quality (the process of collocation is described in Section 3), monitoring data in real time, identifying problems and fixing them, and reviewing data for problems or outliers.

During the study, the functioning of the sensors was checked constantly, both to verify that they were transmitting the data and to evaluate possible unreal measured data. When data do not flow normally for long periods, it is important to check the sensor where it was installed. At times, the sensors needed a reboot or, in one case, to be replaced with a backup.

METHODOLOGY

The methodology can be divided into three major components: collocation, fixed sensors, and mobile sensors. The study was designed and followed the guidance for air monitoring developed by the U.S. Environmental Protection Agency to ensure collection of high-quality data (U.S. EPA 2002). All measurements were made between September and November 2018. Box 1 presents some general information about the study.

Box 1 | **Study Overview**

Area: Historic city center of São Paulo

Pollutant: Particulate matter 2.5 ($PM_{2.5}$)

Measurements: Collocation, fixed sensor study, and mobile sensor study

Duration: September 26–November 23, 2018

Other data: CETESB (Environmental Company of the State of São Paulo) monitoring station data

Outcomes sought: Evaluation of low-cost sensors effectiveness

COLLOCATION: PRE- AND POSTPROCESSING

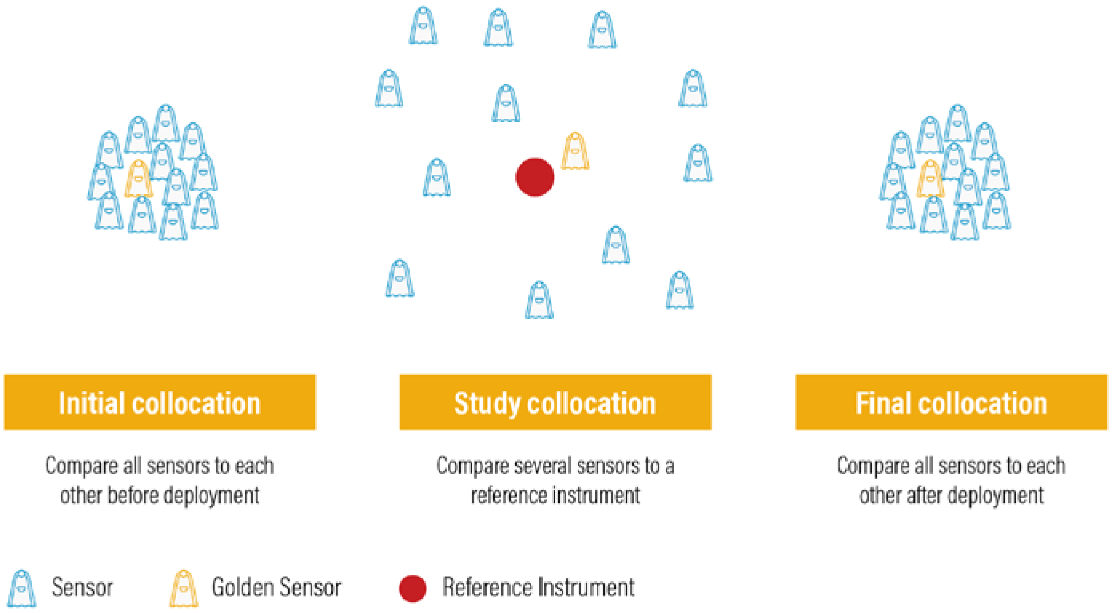
A collocation is the process of comparing data collected from a sensor system with other sensor systems, or with data collected by a known reference instrument, for the purpose of evaluating their quality. Low-cost sensors in general cannot be directly calibrated, so the sensor data are adjusted using regression equations generated from the collocation studies. As shown in Figure 5, one initial (pre-data collection processing) and one final (post-data collection processing) collocation were done for all sensors. During the study, a continuous collocation was performed with a sensor (called the golden sensor) located next to a reference station. This golden sensor served as reference for other low-cost instruments, with their measurements being adjusted at the end of the study. The golden sensor was chosen among the instruments with best correlation with their peers in the pre-collocation. The reference station used was in Dom Pedro II Park, which has automatic measurement equipment using the beta radiation method. The monitoring station is operated by CETESB and is the closest to the area studied. This approach was important to compare how well sensors were measuring relative to each other and to the reference.

The collocation was conducted at the beginning and end of the study for at least 24 hours each time. The sensors were located as close as possible to each other to measure similar atmospheric conditions, yet with enough separation that they did not interfere with each other. To run this experiment, a secure and accessible two-square-meter area, with power connection available, was used for the 30 sensors.

For the collocations, Airbeam2's communication methods of Wi-Fi and cellular were used to check both modes' reliability. The tests showed that the communication method did not alter the concentration measurements or the amount of data.

After the initial collocation, 21 sensors were chosen for the Car-Free Friday study (18 for deployment and 3 as spares in case of theft or damage). Some of the nonselected sensors were set aside due to operational difficulties and others due to lower correlation identified in the initial collocation.

Figure 5 | **Collocation Phases**



Source: Authors.

Figure 6 | **AirBeams Installed at the Top of the Monitoring Station**

Source: Virginia B. Tavares/WRI Brasil.

Eleven sensors were installed on public buildings in the central part of the city. These sensors were used as fixed sensors. With the support of CETESB, another two sensors were installed near the Dom Pedro II Park air quality monitoring station (Figure 6) to provide continuous collocation with a reference instrument (one is the golden sensor, and the other is a backup in case of problems with the golden sensor). In total, 13 sensors were installed in the fixed mode.

In addition to the fixed sensors, five mobile sensors were used to measure $PM_{2.5}$ on different routes. Study participants carried a sensor (Figure 7) and walked a specific route. Mobile measurements occurred on two Car-Free Fridays (September 28 and October 26) and on three regular Fridays (October 5, October 19, and November 9).

The objective with collocations was to compare all sensor systems to ensure that an individual sensor system performed similarly to its peers. Initial and final collocations were used to determine how these

Figure 7 | **Study Participant Carrying a Sensor**

Source: Virginia B. Tavares/WRI Brasil.

sensors performed during the study period. If a sensor's performance worsened compared to the others, this meant that there were problems with its operation that would require adjustments in the data collected.

In this study, as there was no significant change between the sensors' correlation in the initial and final collocations, a regular adjustment based on the golden sensor was applied to the results. This adjustment was the same during the entire study for each sensor. That made all sensors' data internally consistent, which is necessary to compare data from different locations and times of the day.

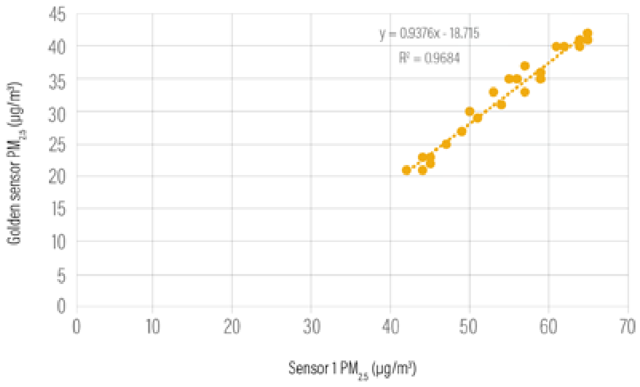
For this specific intervention, the objective was to verify the difference between the areas, not to measure the absolute concentration itself. For that reason, the assessment with the monitoring station served to confirm the low-cost sensors' reliability, but it wasn't used as an adjustment[2] equation to relate other sensors to the reference instrument data.

Linear regression equations were used to adjust the data. Measurement standardization allowed comparison of results with the golden sensor. Equation 1 presents the format of the generated equations.

Sensor (calibrated) = Slope * Sensor value + Intercept (1)

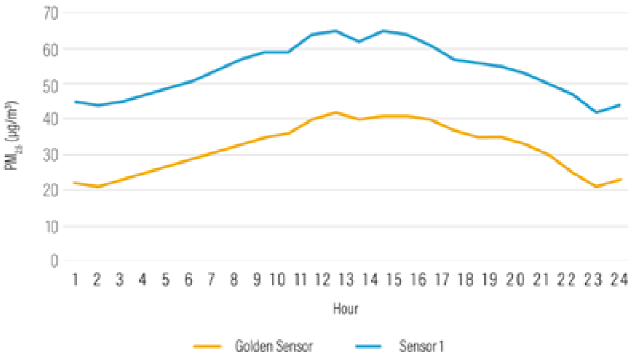
Figures 8, 9, and 10 exemplify the data adjustment process using the golden sensor (not using real data collected in the project). The process begins with the development of a scatter plot that compares the pollutant concentrations measured by the golden sensor with the concentrations detected by each sensor, generating the equations for adjustment (Figure 8). From this equation, the data are adjusted. Figure 9 shows an example of measurements before adjustment. Figure 10 illustrates data after measurement adequacy was checked by the regression equation.

Figure 8 | **Example of Scatter Plot to Generate Adjustment Equations**



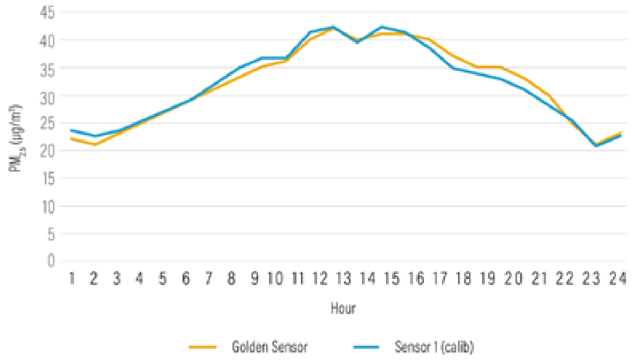
Source: Authors.

Figure 9 | **Example of Measurement Data Before Adjustment**



Source: Authors.

Figure 10 | **Example of Measurement Data After Adjustment**



Source: Authors.

FIXED SENSOR SYSTEM STUDY

The locations of fixed sensors were chosen such that some sensors would be near the area with closed streets and some outside this area, where the impacts were not expected to be so direct. To verify differences in local $PM_{2.5}$ concentrations, the sensors were divided into two distinct zones. The zone where the initiative takes place was called the Car-Free Zone (CFZ). Eight fixed sensors were located in the CFZ and appear in blue in Figure 11.

Sensors outside this area were placed in the comparison group, called the Non-Car-Free Zone (NCFZ). Five fixed sensors were installed in the NCFZ, including equipment located near the CETESB monitoring station, and appear in yellow in Figure 11.

Comparisons between zones were made during the same periods of time. Since different days do not have the same weather conditions, direct comparison of their PM concentration levels can lead to false conclusions. For example, a Friday not part of the initiative may have lower $PM_{2.5}$ concentrations than a Car-Free Friday, but that does not mean that closing roads to cars increases pollution levels, since several external factors affect the pollutant concentration.

In order to analyze both the reliability of the sensors and the PM concentrations in the study area, it was necessary to verify whether the amount of data was sufficient to draw conclusions about the validity of the averages used. Data may be lacking due to system problems that lead to measurements being taken at a slower rate than normal, or operational problems such as power outages. When sensors did not have enough data on a given analyzed Friday, these data were excluded from the analysis. Apart from that, for all sensors, outlier data were eliminated based on cutoffs generated by adjusting statistical distributions, using inverse cumulative probability for 0.99865.

All sensors in the same zone were considered as a network of sensors, gathering all their hourly data and then using an hourly average per zone. The averages of $PM_{2.5}$ concentration were calculated by zone (CFZ and NCFZ), and then the zones were

Figure 11 | **Location of Fixed Sensors in São Paulo City Center**

Source: Authors.

compared for each hour of the day. For each day, the percentage differences between zones were calculated, using the difference-in-differences method. Then statistical tests were performed to check the differences between each day and others. Data from all Fridays measured during the study period, except holidays, were compared, producing data for two Car-Free Fridays and three Non-Car-Free Fridays.

MOBILE SENSOR SYSTEM STUDY

Mobile sensors can be a useful way to collect data at many different locations. The AirBeam2 was paired with a mobile phone to get a GPS signal. For this mode of sampling, the sensor records one-second data, capturing the time and location of the measurements. Using mobile mode, an enormous quantity of data distributed on the city center's streets was collected. The main goal with mobile data was to verify the potential of data visualization for on-the-ground interventions.

Five routes were designed to collect mobile measurements in both Car-Free and Non-Car-Free Zones. Each study participant would walk their route three hours per day: in the morning (between 9 a.m. and 10 a.m.), in early afternoon (between 12:30 p.m. and 1:30 p.m.), and in late afternoon (between 4 p.m. and 5 p.m.). The same routes were taken on two Car-Free Fridays (September 28 and October 26) and on three regular Fridays (October 5, October 19, and November 9).

RESULTS

COLLOCATION

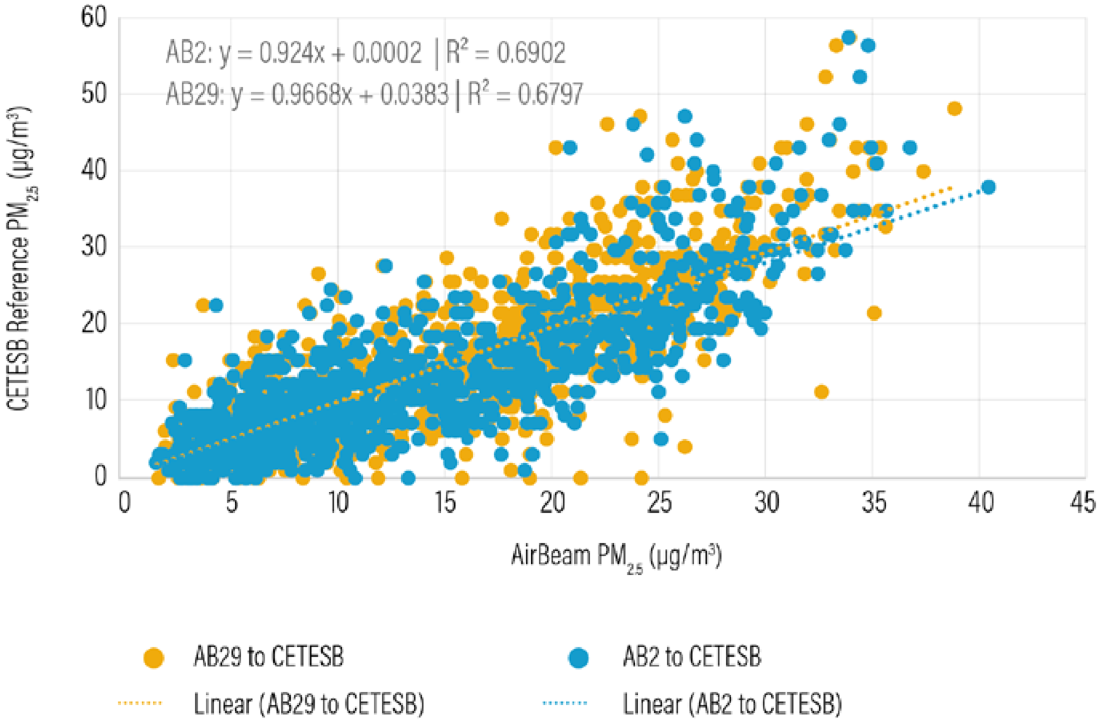
The first validation step of the project's results was to verify the sensors' reliability. This verification was essential to ensure that the analysis carried out would be valid and credible.

Correlation analysis showed that all sensors compared to the reference (or "golden") sensor using hourly averages were well correlated (R^2 equal to or greater than 0.94). Sensor performance in pre- and post-collocation studies were similar, meaning that no further adjustments were needed to adapt the results presented.

The two sensors that were placed near the CETESB monitoring station in Dom Pedro II Park showed reasonably consistent results when compared to the reference instrument. Initially the sensors named AB1 and AB29 (golden sensor) were placed near the station. During the first week AB1 stopped working. It was replaced with AB2 and no longer used in the study. AB29 was installed on September 27, while AB2 began operating on October 4. Both were removed on November 23.

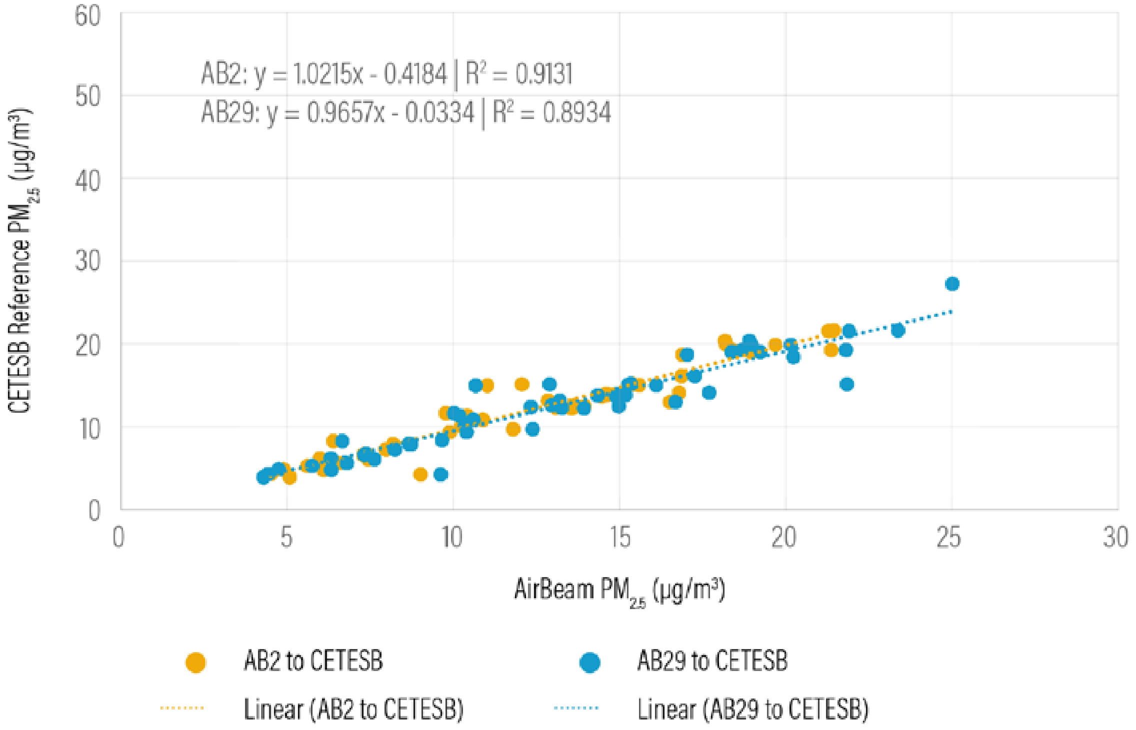
The sensors ultimately showed a reasonable correlation with the reference instrument. For the hourly means the R^2 was approximately 0.68, while for the daily means the R^2 was approximately 0.9, as shown in Figures 12 and 13. These values demonstrate that the measurements performed by the sensors were reliable.

Figure 12 | Scatter Plot of Average Hourly Concentrations



Source: Authors.

Figure 13 | Scatter Plot of Average Daily Concentrations



Source: Authors.

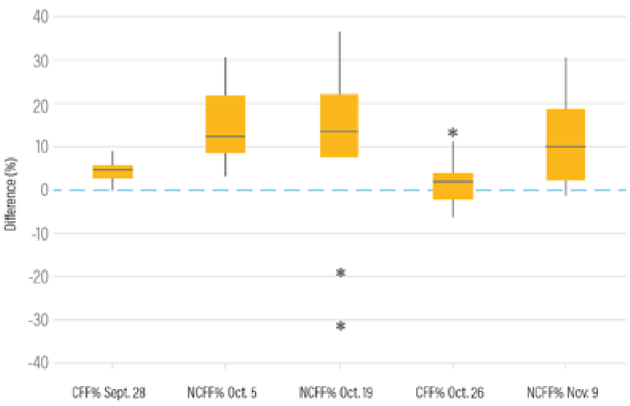
FIXED SENSOR SYSTEM

For the fixed sensor study, three sensors were eliminated due to technical problems. Two of these were the sensors located at the CETESB monitoring station: one had to be replaced since it stopped working (for unknown reasons) in the first days of the study; the other didn't have enough daily data on one of the Fridays. The third one was located in the Car-Free Zone and also was discarded due to lack of data. Other sensors also had problems collecting data, such as reporting data less frequently or power outages and consequent complete loss of battery power, but that didn't invalidate the averages obtained for those days.

In total, of the eight fixed sensors placed in the CFZ, seven were used for the data analysis. For the NCFZ, four of five sensors were used, including the golden sensor located next to the CETESB reference monitoring station.

Measurements have shown that, on all Fridays, the $PM_{2.5}$ concentration in the CFZ was slightly higher than in the NCFZ. The analysis was conducted from 6 a.m. to 5:59 p.m., to match the times of the car-free initiative. Paired t-tests were used to compare mean differences between days. On Car-Free Fridays, the difference between the zones was smaller than on other Fridays. The results show a significant difference between Car-Free Fridays (CFFs) and Non-Car-Free Fridays (NCFFs) in all cases (each day compared to another), when eliminating outliers. This result suggests that the Car-Free Friday initiative might reduce $PM_{2.5}$ concentration in that area. However, as measurements were taken on only two Car-Free Fridays, more studies are needed to statistically validate these results. Figure 14 shows the percentage difference between the zones on each day, calculated as (CFZ or NCFZ)/CFZ.

Figure 14 | **Percentage Difference between Zones for Fixed Sensors**



Source: Authors.

MOBILE SENSOR SYSTEM

For the mobile sensor study, data on five Fridays (two CFFs and three NCFFs) were collected, using five sensors on each of these days. Five participants walked routes in both Car-Free Zones and Non-Car-Free Zones. This generated an abundance of data, demonstrating the potential of data visualization insights for this type of project.

Figure 15 shows raw data generated by sensors, before cleaning procedures, while Figure 16 shows daily averages organized per street segment, for a CFF and an NCFF, respectively. The scale was constructed using minimum and maximum concentration averages for the day. Color scaling helps to identify differences within and between regions and segments. Despite the limited number of days analyzed, having such visual analysis shows some interesting features worth deeper investigation:

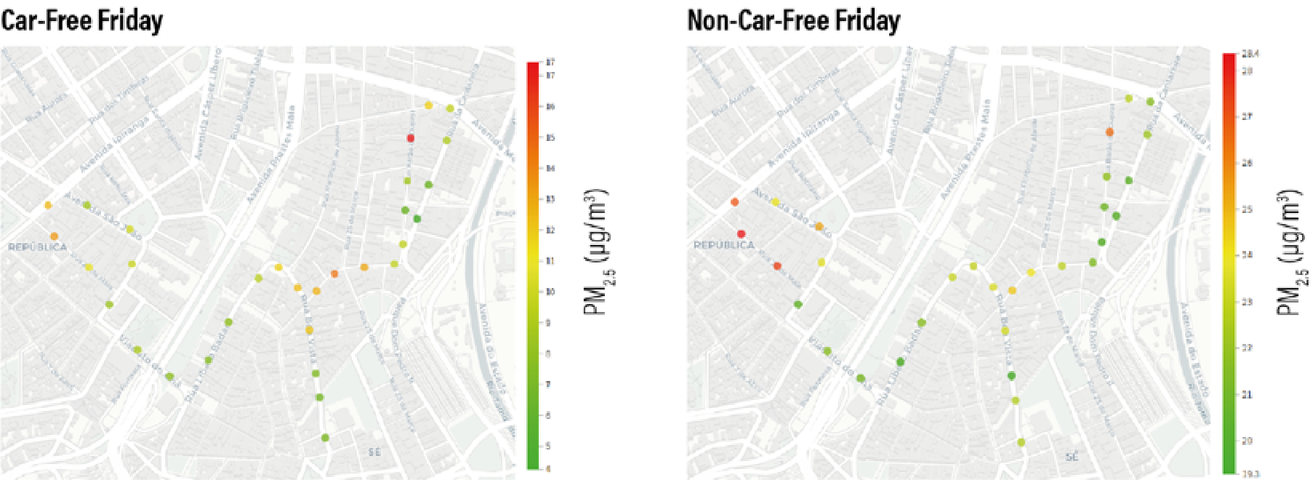
- Relatively higher $PM_{2.5}$ conditions outside the Car-Free Zone (left dots) on Car-Free Fridays may indicate more pollution from another source (perhaps more traffic congestion). Detailed traffic counts could help confirm this observation.
- Persistently higher $PM_{2.5}$ concentrations at a fixed spot occurred on all days and may indicate a very local "hot spot," which could be investigated by looking for local sources of $PM_{2.5}$ in that area.

This type of data visualization enables us to better identify sources of pollution in different areas.

Figure 15 | **Mobile Data Generated in One CFF**

Source: Authors.

Figure 16 | **Average Daily Concentrations per Street Segment**


Car-Free Friday

Non-Car-Free Friday

Source: Authors.

LESSONS LEARNED

This project has produced several lessons learned that are worth sharing for future deployments of low-cost sensors:

- **Pollutant analyzed for the type of urban intervention chosen:** Other pollutants emitted more directly by vehicles impacted by CFF, such as CO or NOx, might have shown a greater impact on pollutant concentrations. In Brazil, it is more common for trucks and buses to use diesel, which emits more $PM_{2.5}$. Cars and motorcycles (vehicles that have more traffic restrictions on CFFs) generally use other types of fuel that emit more of other pollutants. These factors are important to analyze while planning the scope of project.
- **Atmospheric conditions:** It is important to consider expected weather patterns when planning such a study. For example, winter versus summer seasons, or windy conditions and months when heavy rainfall is common. Those changes might affect the evaluation of a given initiative, generating different results.
- **Logistical issues:** This study started with 30 devices, which generated a large amount of data. It was important to maintain a good management and logging system to keep track of them and keep everything labeled and documented. Small procedures that require little effort for one or two devices can take much longer when many sensors are involved. Also, preparing a site to install a low-cost sensor took several weeks, so it was important to plan accordingly and budget enough time in the project schedule.
- **Data analysis:** This short-term study produced a wealth of data with one-minute fixed values and one-second mobile values. Extracting and processing this information required identifying software to extract the data from the air sensor web database, creating rules on how to average data to ensure completeness and representativeness, and performing statistical analysis for the assessment.
- **Collocation with the reference instrument:** Comparison of the sensor data with the CETESB monitoring station was very important to verify the instruments' accuracy. The sensors were installed at the station for about two months, collecting enough data to enable a strong statistical analysis to evaluate them. It is especially important to collocate the sensors with a reliable reference instrument to analyze the study's accuracy.
- **Awareness building:** By engaging with officials at city government, fixed sensors could be installed in government buildings for an extended period, and have access to power outlets. Moreover, government employees were genuinely interested in learning more about the sensors—how they worked, what they measured, and why the study was being conducted. This form of awareness-building can prove very valuable for moving the needle from awareness to action, and also reinforce for city agents the importance and the value of programs like Car-Free Friday.

CONCLUSIONS

The study generated valuable lessons learned that might help cities to design and better prepare studies using low-cost sensors. The low-cost instruments have shown a good correlation among them. When compared to a reference instrument, such as the CETESB monitoring station, the Airbeam2 instrument compared well and consistently with other studies. When combined with other information, the sensors can give good indications of PM concentrations. Sometimes the sensors collected incomplete data, which can present a challenge to more robust use, but they are a useful complement to traditional monitoring station networks. Because these devices are a new technology, we recommend more studies to validate low-cost sensors' application and reliability.

The use of low-cost sensors could help to build public awareness and catalyze smarter cities. As their technology improves, more studies are conducted, and lessons learned are shared, the application of low-cost sensors could move, in the near future, from piloting to standard operations. Sustainable mobility initiatives, like Sao Paulo's Car-Free Friday, could benefit from such a data evolution.

The deployment of low-cost sensors to analyze Car-Free Friday indicates that the initiative might have impacts on local PM concentration, despite its restricted geographic area. In the fixed sensor study, considering only the Fridays measured during the study, a significant statistical difference between the $PM_{2.5}$ concentrations on Car-Free Fridays compared to Non-Car-Free Fridays was observed. However, due to small sampling (five days) it cannot be concluded that the initiative has effective impact on PM concentrations. The use of mobile data also demonstrated good potential for further analysis, helping to localize places that have higher PM concentrations.

Future studies to evaluate the intervention should use a greater sample of days to be able to offer statistical conclusions about the impacts of the initiative. Traffic behavior in São Paulo could also be analyzed to see if Friday patterns are similar to other weekdays, so more days can be used for this analysis. Finally, this specific initiative could be evaluated with other types of pollutants, since its effect on particulate matter must be lower considering that cars and motorcycles usually use gasoline in Brazil.

ENDNOTES

1. Sensors are not stand-alone devices (in order to measure, they must be incorporated into an instrument), and, depending on how an instrument is designed, the sensor may perform well or poorly. We use the terms *low-cost air quality sensors* and *low-cost air quality instruments* as synonyms, however, since the first is most used in the literature.
2. The adjustment is used as a calibration, but instead of calibrating the sensors before study, their measurements were adjusted afterward.

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WRI Brasil is a research institute that transforms big ideas into actions to protect the environment and foster Brazil's prosperity in an inclusive and sustainable fashion. It is focused on research and applications of sustainable solutions oriented towards climate, forests, and cities. WRI Brasil combines technical excellence with political articulation and works in close collaboration with governments, private companies, universities and civil society.

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