Air Quality Mapping Using PM2.5 Sensors on Urban Buses

Inés González-de-Castro, Mar Viana, José Javier Ramasco, Aina Maín-Nadal, and Teresa Moreno

***Abstract*—Six low-cost air quality sensors were installed on the front roof area of three buses to enable real-time monitoring of air quality across the city of Valladolid (Spain) over a seven-month period, capturing variability in meteorological conditions and emission sources. Prior to deployment, the sensors were placed at a reference station in Barcelona (Spain) for validation and calibration. Measurements deviating by more than 30% from reference values were discarded, and correlation coefficients (R^2) were calculated. After the monitoring campaign, the calibration procedure was repeated. The results ($R^2 = 0.85$) suggest that bus-mounted sensors can effectively support real-time detection of urban air quality changes and contribute to detailed air quality mapping. Integrating data from reference air quality monitoring networks (AQMNs) with low-cost sensor (LCS) systems can strengthen evidence-based policymaking and help refine regulatory frameworks aimed at reducing urban air pollution.**

***Index Terms*—Low-cost sensors, mapping, PM2.5, sensors, urban air quality.**

I. INTRODUCTION

THE effects of particulate matter (PM) on human health and air quality are well established. Both short-term and long-term exposure to PM2.5 and PM10 (particles smaller than 2.5 and 10 μm, respectively) are linked to increased respiratory and cardiovascular morbidity and to premature mortality [1], [2], [3]. Exposure to PM2.5 has also been associated with an 8.5% increase in overall cancer incidence, with elevated risks specifically for lung cancer and adenocarcinoma [4]. Similarly, PM2.5 exposure is associated with a 2.5% increase in mortality from all cancers combined, including lung and breast cancer. Globally, air pollution accounts for an estimated 9–12 million deaths per year [5]. A major contributor to air pollution is PM2.5 originating from vehicles, industrial activities, and smoke from forest fires; these sources represent a major driver of population-level exposure to PM2.5 and associated health risks [6]. Beyond human health, PM also has substantial environmental impacts, affecting both ecosystems and climate [7]. PM is a particularly complex pollutant due to 1) the diverse mixture of anthropogenic and natural emission sources, and 2) the high proportion of secondary PM, particles formed in the atmosphere from gaseous precursors rather than being emitted directly [8], [9].

Rapidly increasing urbanization and evolving mobility needs are creating new transport challenges (e.g., personal electric devices, ridesharing), which require data-driven decision-making tools. These tools can support a wide range of air quality strategies, from the design of effective low-emission zones (LEZs) to helping individuals reduce their exposure by selecting low-pollution commuting routes.

Most modern cities face significant air quality problems, largely due to emissions of gases and PM from anthropogenic sources such as road traffic. Because these emissions occur at street level and in close proximity to people, understanding real exposure is crucial. However, fixed official monitoring stations, while providing high-quality measurements, offer only limited spatial coverage. As a result, they provide an incomplete picture of the pollution levels that individuals actually inhale across the urban environment. In this context, portable, vehicle-mounted monitoring equipment offers a valuable alternative. As the vehicle moves through the city, sensors can map concentrations of various air pollutants, capturing spatially resolved dynamic information. This approach enables the creation of high-quality, dense air pollution maps and has already been successfully implemented in several European contexts, including Zurich, the Netherlands, and Belgium [10], [11], [12]. Although low-cost air quality sensors typically produce medium to low-quality data, albeit with high temporal and spatial resolution [13], their accuracy can be substantially improved using appropriate data filtering and processing algorithms, including machine-learning methods such as support vector regression (SVR) and Random Forest (RF) [14], [15]. As a result, despite their lower baseline accuracy, low-cost monitors, once calibrated and processed, have proven effective for high-resolution urban air quality mapping [12].

The main objective of this study is to evaluate how mobile air quality sensors can substantially enhance our understanding of urban air pollution and population exposure. Because buses account for the majority of public transport journeys in the EU (56%; http://www.uitp.org/key-eu-statistics), this mode of transport was selected as the platform for mobile monitoring. The insights gained from this pilot study could be extended to

Received December 18, 2025; revised February 9, 2026; accepted March 6, 2026. This work was supported by the NEXT4MOB Project through the Spanish Ministry of Science and Innovation under Grant PLEC2021-007824. *(Corresponding author: Teresa Moreno.)*

Inés González-de-Castro, Aina Maín-Nadal, and Teresa Moreno are with the Institute for Environmental Assessment and Water Research (IDAEA-CSIC), 08034 Barcelona, Spain (e-mail: ines.gonzalez@idaea.csic.es; aina.main@idaea.csic.es; teresa.moreno@idaea.csic.es).

Mar Viana is with the Institute for Environmental Assessment and Water Research (IDAEA-CSIC), 08034 Barcelona, Spain, and also with the Subdirección General de Prevención de la Contaminación, 28071 Madrid, Spain (e-mail: mar.viana@idaea.csic.es).

José Javier Ramasco is with the Instituto de Física Interdisciplinar y Sistemas Complejos IFISC (CSIC-UIB), 07122 Palma de Mallorca, Spain (e-mail: jramasco@ifisc.uib-csic.es).

This article has supplementary downloadable material available at https://doi.org/10.1109/JIOT.2026.3672932, provided by the authors.

Digital Object Identifier 10.1109/JIOT.2026.3672932

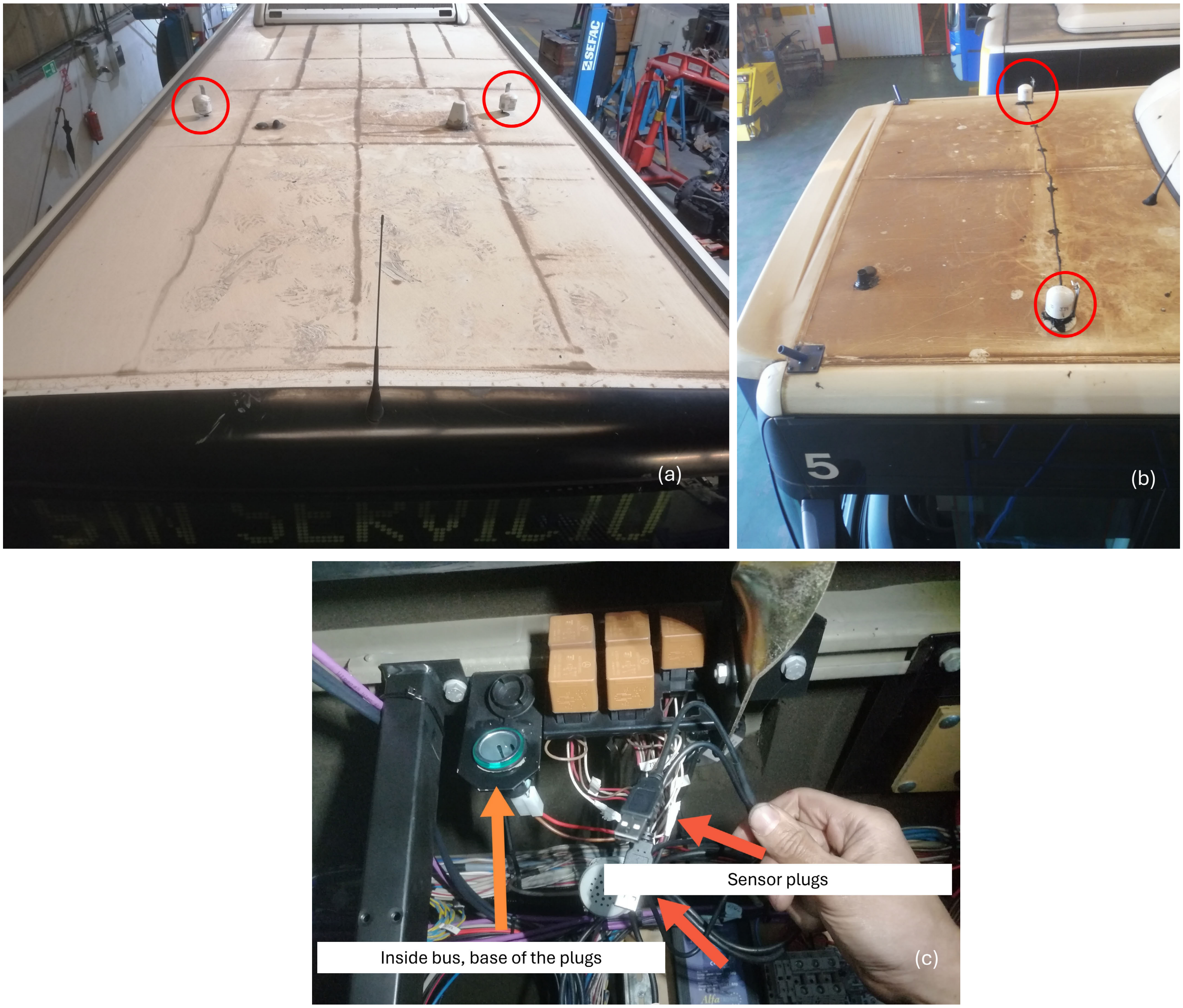

Fig. 1. (a) and (b) Location of air quality sensors on the front of the bus roofs, and (c) connection of the sensor installation inside the bus.

other urban environments to support the validation of dispersion models, the design of effective mitigation strategies, and improved public communication, particularly in the context of the new Air Quality Directive.

II. MATERIALS AND METHODS

The study was conducted in the city of Valladolid from September–October 2022 to May 2023, located in northwest Spain (41°39’05.2”N, 4°43’50.4”W). In 2022, the city had a population of 295 639 inhabitants, an area of 197.9 km^2, and a population density of 1514.4 inhabitants/km^2. Air quality monitoring combined data from fixed EU reference stations’ air quality monitoring networks (AQMNs) with measurements from portable PM2.5 sensors installed on public buses.

PurpleAir, a 2-min intervaloptical portable monitor, [16] was selected to measure PM2.5 concentrations; each sensor was identified with a code formed by the letters JJ followed by a number from 1 to 8. After an initial calibration (see below), two monitors were deployed on the front roof area of 3 buses (Fig. 1). This placement minimized potential cross-contamination from the exhaust pipe and enabled the generation of detailed air pollution maps along multiple routes designed to maximize spatial coverage across the city (Fig. 2). Urban public buses operate daily from 06:00 to 23:00-CET, providing extensive temporal and spatial coverage for monitoring activities.

Air quality monitoring was conducted over a 7-month period to capture variability in meteorological conditions and emission patterns (e.g., holiday-related changes). Each portable monitor contained two sensor units (channels A and B) used for quality control and outlier detection. The two channels were compared, and values differing by more than 30% were discarded. After validation, each monitor produced a single consolidated data stream. Before deployment, the portable monitors were co-located at the “Palau Reial” reference station (Barcelona) for six days in September to perform sensor

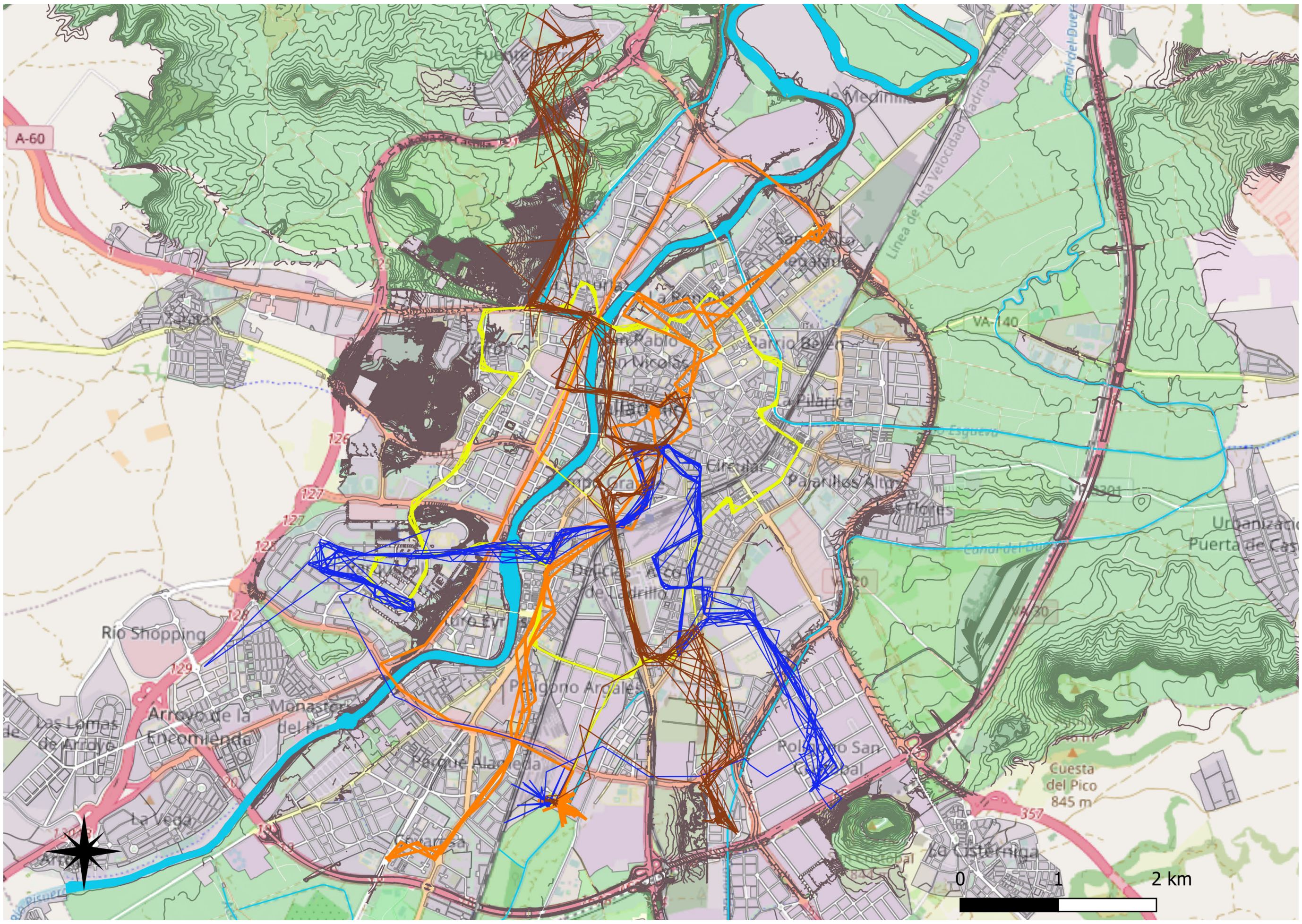

Fig. 2. Bus routes. Brown: Bus line 4. Blue: Bus Line 9. Orange: Bus line 1. Yellow: Bus line circular.

validation and calibration. Although the low-cost sensors used in this study were calibrated in Barcelona, a coastal city characterized by higher relative humidity, the measurements were conducted in Valladolid, which has a more continental and generally drier climate. Optical PM2.5 sensors are known to be sensitive to relative humidity due to the hygroscopic growth of particles, which may lead to overestimation under humid conditions. Therefore, applying a calibration derived from a more humid environment could introduce a systematic bias in absolute PM2.5 concentrations. However, given the typically lower relative humidity in Valladolid, this effect is expected to be reduced. Furthermore, the main focus of this study is on temporal variability and relative changes in PM2.5 rather than on absolute concentration values, which are less sensitive to humidity-related biases. Nevertheless, this aspect should be taken into account when interpreting the results.

Each sensor was corrected using an individual regression model derived from the co-location period, improving agreement with the reference station and supporting outlier detection. More than 30% diference between both channels. The correlation (R^2) between sensor readings and reference concentrations from the local AQMN was calculated. The calibration was repeated at the end of the monitoring campaign, during a second co-location period of seven days in May. Because no significant variations in relative humidity were expected across the city, the potential bias associated with hygroscopic particle growth, known to affect portable optical monitors [17], was considered negligible. Consequently, the sensors deployed along the different bus routes were deemed comparable.

A smartphone was installed on each bus to track sensor locations using the global positioning system (GPS) and to enable real-time monitoring of all sensors via Wi-Fi.

The city of Valladolid operates four EU-reference air quality monitoring stations that measure hourly concentrations of regulated pollutants (PM2.5, NO_2, O_3, NO) in accordance with European reference protocols (Directive (EU) 2024/2881). These fixed stations provide high-quality but low-spatial-resolution data. Temporal resolution varies by pollutant and instrumentation, ranging from 30 min to 1 h for gaseous pollutants and from 1 to 24 h for PM2.5. Data from the network are publicly available at https://www.valladolid.es/es/rccava/datos-red. To support comparison and validation, a portable monitor was also installed at each of the two fixed air quality monitoring stations located along the bus routes. This allowed offline comparison between portable sensor measurements and reference station data to quantify potential deviations.

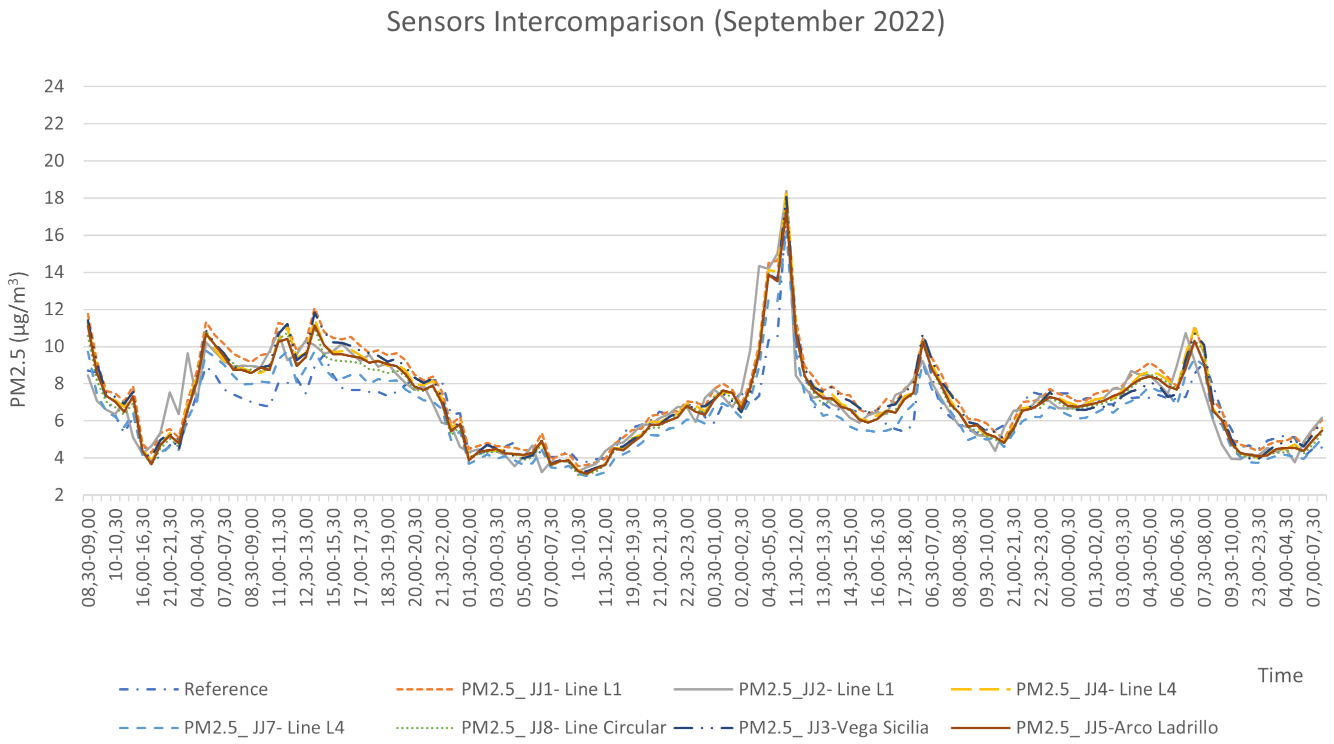

Fig. 3. Sensors intercomparison before the monitoring campaign. "Reference" is the Palau Reial reference station. Correlations of the 30 min average of the sensor.

In total, six portable monitors were installed on three buses, and two additional portable monitors were deployed at the two-reference air quality monitoring stations.

III. Results and Discussion

A. Data Quality

For PM2.5 concentrations, we observed a low intrasensor variability (i.e., high precision), with correlations of 30 min average of the sensor in the order of R^2 = 0.84–0.87 before the campaign, and R^2 = 0.81–0.88 after the campaign (Figs. 3 and S1–S4). Throughout the entire campaign, the sensors operated with full 24-h uptime on all scheduled days. Only two sensors reported errors: one experienced a complete failure (JJ1), and another showed degradation in one of its two channels (JJ3). No maintenance was required during the campaign, except for the sensor with complete failure. The JJ1 portable monitor on bus route L1 was replaced with the Idaea_25 unit due to a malfunction. Because of the need to quickly replace the sensor, the internally used ID code could not be changed. In the case of partial degradation, the sensor was kept in operation using only one channel. In both cases, failures were attributed to normal wear and tear. In addition, the bus operating this route was taken out of service in April 2023 because of technical issues, resulting in no data being available for the final month of measurements for L1.

No significant differences were observed between measurements from the portable monitors and the Palau Reial reference station, both before and after the monitoring campaign, indicating consistent performance across all devices (Figs. S1–S3). Likewise, comparisons with the Arco Ladrillo and Vega Sicilia reference stations (Fig. S5) showed no notable discrepancies, further confirming the reliability and accuracy of the portable monitors across different reference locations.

Although these sensors can be influenced by humidity [18], the relatively low humidity levels in Valladolid during the sampling period suggest that their measurements were minimally affected (Fig. S6).

The eight portable monitors collected over 1.1 million data points between October 2022 and May 2023, with each point representing a PM2.5 measurement recorded at two-minute intervals. After data processing, 68.75% of the measurements (approximately 764 000 data points) were deemed valid (Table I and Fig. 4). As described above, all data points showing a greater than 30% difference between channels A and B were removed [19].

B. PM2.5 Variation

The temporal variability of PM2.5 levels was analyzed by plotting hourly, daily, and monthly data from the mobile measurements using the R package Openair (Figs. 4 and 5), as well as the monthly variability of PM2.5 concentrations (μg m^{-3}) recorded by all mobile sensors (Figs. 4 and S7). Fig. S6 summarizes the temporal availability and variability of PM2.5 measurements collected along different bus routes. The red segments in the lower panels indicate periods with missing or discarded data, mainly caused by mechanical failures, sensor downtime, or route interruptions. In the case of Line 1, the high proportion of missing data reflects extended periods when the bus was not operating, while for Line 9, measurements are

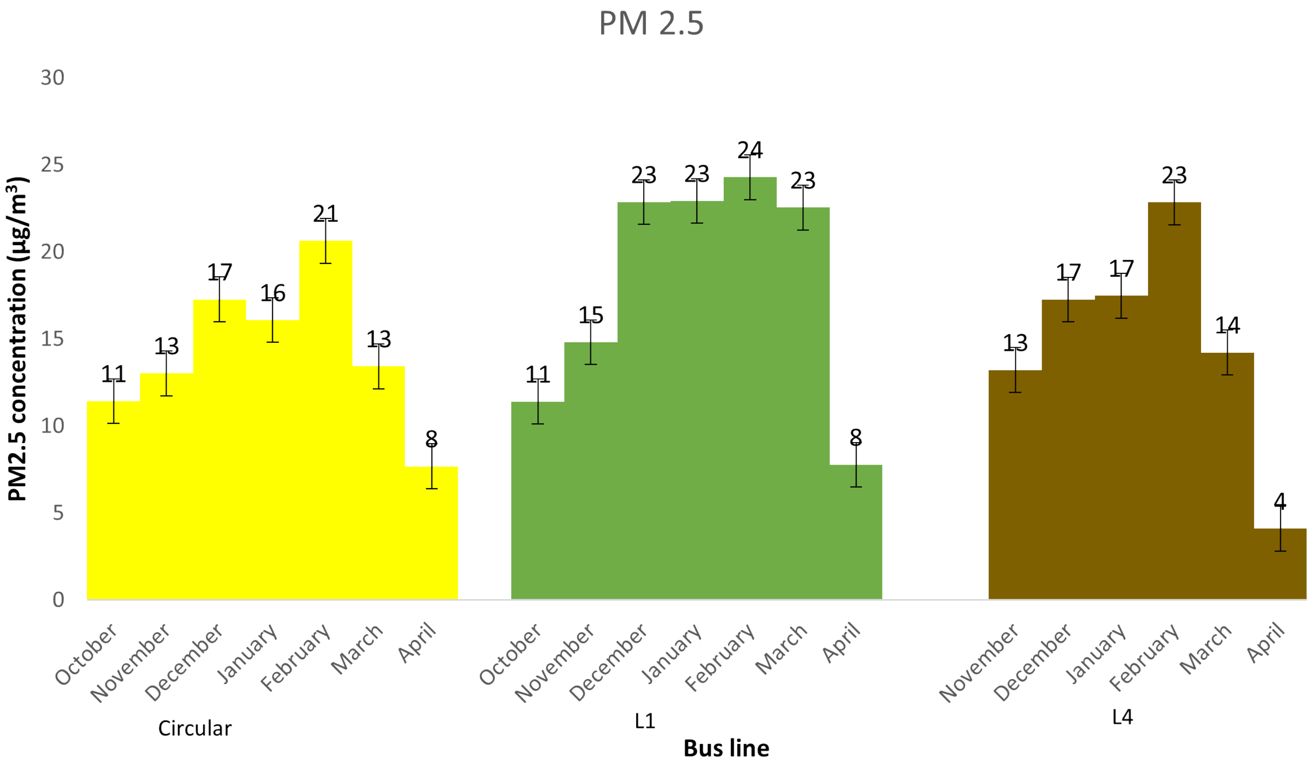

Fig. 4. Bar chart indicating the monthly average PM2.5 (μg/m^3) by bus line from October 2022 to April 2023. Error bars correspond to the standard error of the mean (SEM), reflecting the precision of the estimated mean.

limited to a single month due to the reassignment of sensors to other routes. As a result, these lines provide limited temporal representativeness and are not suitable for direct interline quantitative comparison. Nevertheless, the figure remains useful for illustrating data coverage, identifying gaps in the mobile monitoring strategy, and contextualizing the robustness of the subsequent analyses.

Both analyses show a consistent daily pattern: PM2.5 concentrations decrease around midday, with peaks in the early morning (06:00–09:00) and in the late afternoon to evening (18:00–22:00) (Fig. 5). These peaks likely correspond to increased vehicular activity in and around the bus depots at the start and end of operational shifts, resulting in elevated PM emissions [20].

During the week, PM2.5 levels show variability depending on the bus line. The circular line exhibits a peak on Saturdays, likely due to shopping and leisure activities, with lower values on Sundays and Mondays. A similar pattern is observed on line L4, although this line also shows a PM peak on Tuesdays. Line L1 typically shows higher PM concentrations over the weekend, with lower values during weekdays. Line L9, which was monitored only in October, recorded higher PM levels from Monday to Friday and lower values on weekends. On an annual scale, PM2.5 concentrations were higher during the winter months compared to the summer months (Fig. 4).

To investigate the spatial variation of PM2.5, we mapped daily street-segment exposures between October 2022 and April 2023 to identify areas with consistently higher concentrations and potential recurring hotspots (Fig. 6). The spatial distribution maps reveal a clear heterogeneity in PM2.5 concentrations across the city. While most areas show relatively homogeneous values, several locations consistently exhibit higher PM2.5 levels. These areas are mainly associated with high-traffic corridors, major intersections, and zones with frequent bus stops, where repeated vehicle acceleration and braking occur. The ability to detect such localized increases highlights the potential of mobile sensor deployments to identify specific urban areas with air quality challenges that may not be captured by fixed monitoring stations. The maps reveal that winter months generally exhibit higher PM2.5 levels, particularly in the central and northern parts of the city, with very high values also observed at the bus depot. These results demonstrate that bus-mounted sensors are an effective tool for mapping urban air quality, enabling real-time detection of pollution changes. Such changes may result not only from increased traffic but also from events like roadworks, providing a more detailed and actionable understanding than fixed monitoring stations alone. Integrating portable monitors with the city bus network offers a comprehensive view of air quality across all neighborhoods, supporting more informed decision-making for urban air management.

IV. DESIGN CONSIDERATIONS AND RECOMMENDATIONS

Although sensors provide higher temporal and spatial resolution than the reference station, this comes at the cost of reduced data quality, a higher failure rate (approximately 25% over a 7-month period), and limitations in campaign

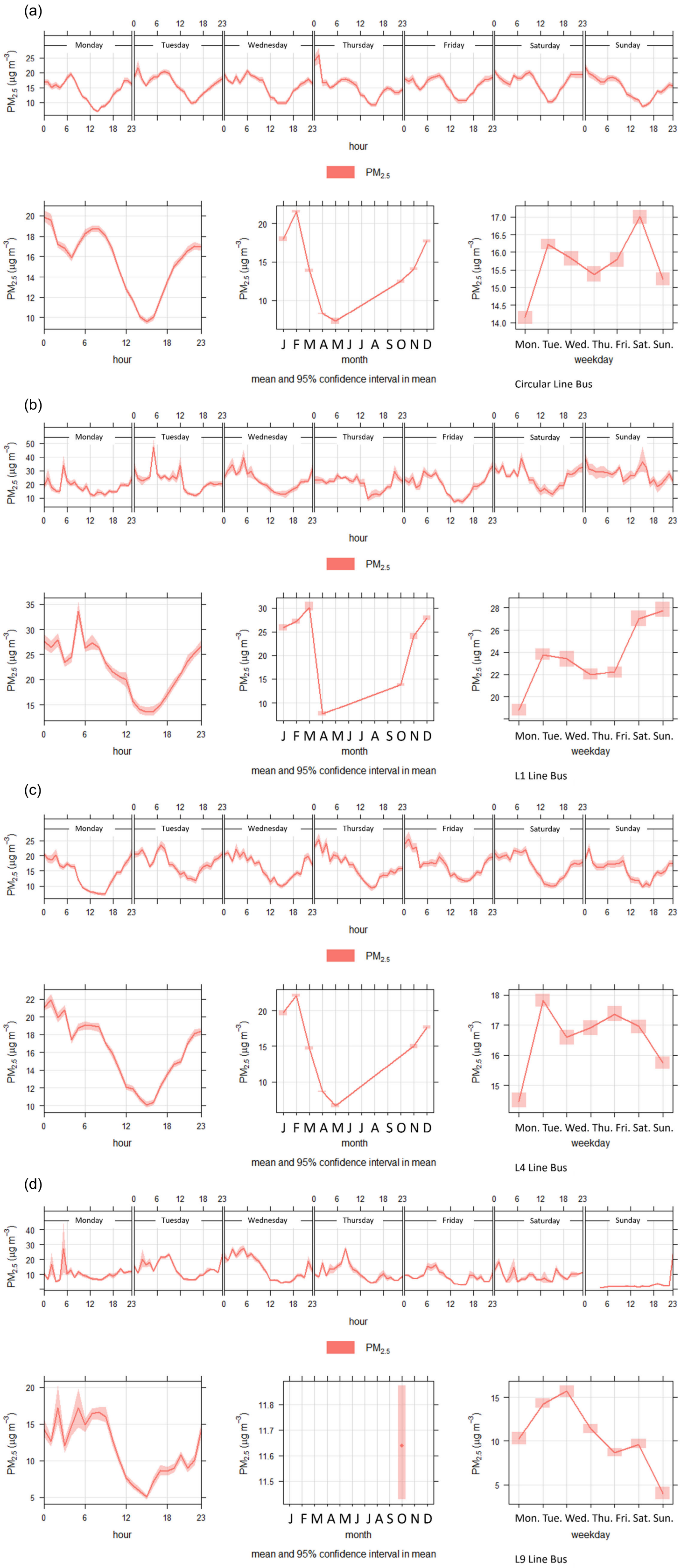

Fig. 5. Hourly, daily, and monthly variability of the PM2.5 (μg/m^3) measurements collected by the mobile sensor fleet (all sensors). (a) Circular line bus, (b) L1 line bus, (c) L4 line bus, and (d) L9 Line bus, which is just one month of data because the bus made a change of route and it started running on Line 4.

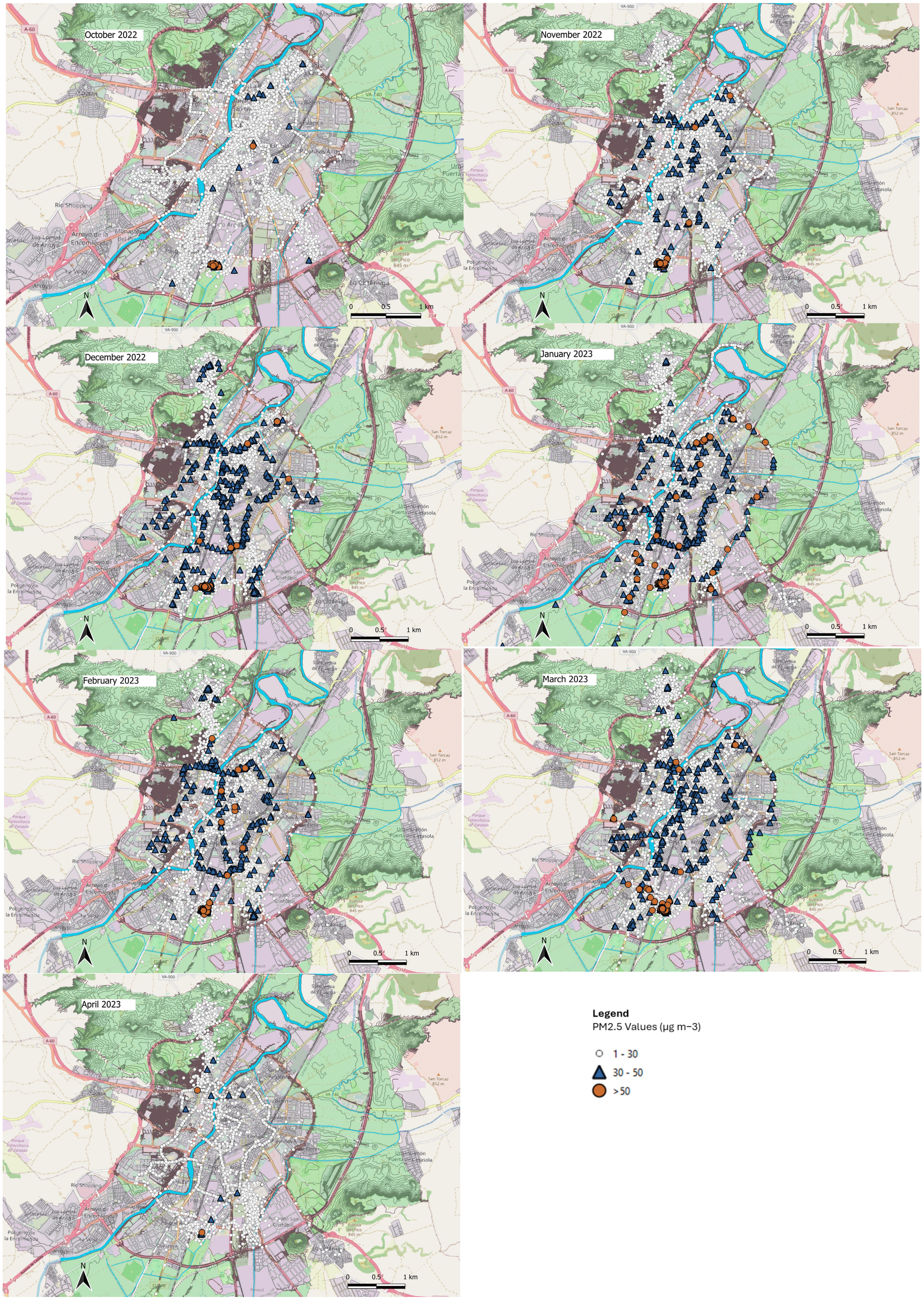

Fig. 6. Spatiotemporal distribution of air pollution in Valladolid city. Maps of monthly collected PM2.5 (μg/m^3) measurements between October 2022 and April 2023. Data collected every 2 min. White circles: PM2.5 values 1–30 μg/m^3; Blue triangles: PM2.5 values 30.1–50 μg/m^3; Orange circles: PM2.5 values > 50 μg/m^3.

TABLE I
Monthly Data Coverage (N) and Summary Statistics (Max and Mean) of PM2.5 (μg/m^3)

Month	Bus route	Sensor	n	PM2.5 max.	PM 2.5 Mean
October	circular	JJ6	13062	92	11.4
	L1	JJ2	8993	151	11.4
	L9	JJ4	8023	318	11.4
November	circular	JJ6	18236	123	13
	L1	JJ2	13219	556	14.8
	L4	JJ4	10565	155	13.2
December	circular	JJ6	13724	328	17.3
	L1	JJ2	9050	439	22.9
	L4	JJ4	15976	477	17.3
January	circular	JJ6	19698	502	16.1
	L1	JJ2	5721	367	22.9
	L4	JJ4	17305	351	17.5
February	circular	JJ6	18953	179	20.6
	L1	JJ2	6737	340	24.3
	L4	JJ4	16474	213	22.9
March	circular	JJ6	18218	252	13.4
	L1	JJ2	7950	550	22.5
	L4	JJ4	16843	260	14.2
April	circular	JJ6	18080	81	7.7
	L1$_{\text{*1-5abril}}$	JJ2	906	55	7.8
	L4	JJ4	15075	124	4.1
Total			272808		

duration. Because of the sensor design, periodic disassembly is required as part of maintenance to ensure proper operation. This maintenance task must be performed approximately once per year to keep both channels synchronized and to prevent large deviations from the reference station.

Sensor failure can be mitigated through adequate sensor coverage, taking into account the failure rates of both the sensors and the buses carrying them. The integration of sensors into buses is a complex task, and if a bus fails or stops operating, data from a pair of sensors may be lost. To address these issues, it is recommended to deploy sensors on multiple buses operating along the same route and to install a pair of sensors on each bus.

Further improvements could be achieved by using sensors with integrated infrastructure for data collection, such as GNSS and GSM. This would eliminate the need for an external device (in our case, a mobile phone), thereby reducing the likelihood of device failure and subsequent data loss.

If a pool of readily available low-cost sensors were maintained, failing sensors could be replaced quickly, reducing downtime and enabling longer and more reliable measurement campaigns.

Finally, when deploying these sensors in humid regions, it is important to apply appropriate correction models [18].

V. Conclusion

Deploying air quality sensors on buses proved to be an effective approach for real-time monitoring across the different neighborhoods of Valladolid. These mobile sensors offered a more detailed and comprehensive view of local air quality dynamics than fixed stations, allowing the identification of pronounced spatial heterogeneity and localized PM2.5 hotspots within the urban area, capturing variations linked to traffic congestion, roadworks, and topographical features such as steep streets. However, the analysis also highlighted the importance of data availability and operational continuity, as gaps in sensor coverage can limit the temporal representativeness of some routes and should be explicitly considered when interpreting mobile monitoring results. Importantly, comparisons with the Arco Ladrillo and Vega Sicilia reference stations showed no significant differences, confirming that bus-mounted sensors provide reliable and consistent measurements while substantially enhancing spatial coverage. However, installing the sensor anchoring system on the buses is complex, making it challenging to replace sensors in the event of malfunction or bus downtime, which can last for extended periods. It is therefore recommended to have backup sensors and to deploy duplicate units on each bus to identify and correct potential deviations.

The results indicate that PM2.5 concentrations increased during the colder months, consistent with the literature [21], due to thermal inversions that limit pollutant dispersion. The highest pollution levels were observed in the coldest months, when frequent thermal inversions and weak wind conditions hinder vertical air mixing and the effective dispersal of pollutants. Additionally, PM2.5 levels were lowest in the afternoon and highest at night, when the planetary boundary layer is thinner, trapping pollutants near the surface. These dynamics significantly influence both diurnal and seasonal patterns of air pollution.

Integrating data from reference AQMNs with low-cost monitoring systems (LCS) can enhance the quality of evidence for policy-making and support the development and adjustment of regulatory frameworks aimed at reducing urban air pollution. In particular, the ability to identify localized air pollution hotspots provides actionable information for targeted mitigation strategies at the neighborhood or street level.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the "*Red de Control de la Contaminación Atmosférica del Ayuntamiento de Valladolid* (RCCAVA)" for allowing the installation of additional sensors within their fixed-station monitoring network, and to the public transport company AUVASA (Adrián Rodríguez) for their support and collaboration in the project by enabling the deployment of mobile sensors on urban transit buses.

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