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Paolo Castello, Carlo Muscas, Paolo Attilio Pegoraro, Davide Sitzia, Sara Sulis

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Influence of Apparent Wind on Particulate Matter Monitoring through Low-Cost Sensors

Paolo Castello
Dept. of Electr. and Electron. Eng.
University of Cagliari
Cagliari, Italy
paolo.castello@unica.it

Carlo Muscas
Dept. of Electr. and Electron. Eng.
University of Cagliari
Cagliari, Italy
carlo.muscas@unica.it

Paolo Attilio Pegoraro
Dept. of Electr. and Electron. Eng.
University of Cagliari
Cagliari, Italy
paolo.pegoraro@unica.it

Davide Sitzia
Dept. of Electr. and Electron. Eng.
University of Cagliari
Cagliari, Italy
davide.sitzia@unica.it

Sara Sulis
Dept. of Electr. and Electron. Eng.
University of Cagliari
Cagliari, Italy
sara.sulis@unica.it

Abstract—Recently, there has been a growing awareness of the importance of particulate matter (PM) monitoring due to its negative impact on public health and the urban environment. The proliferation of fixed and mobile monitoring stations based on low-cost sensors is continuing, as they provide a cost-effective solution capable of increasing the spatial resolution of measurements. However, when installed in vehicles as well as in public transportation systems, these devices are subject to the influence of apparent wind, which affects the incoming airflow and, consequently, the suspended particles in the air. In order to evaluate this phenomenon, this study investigates and quantifies the effect of apparent wind on the PM measurements of three different models of low-cost PM sensors in a laboratory setting. Sensors showed different sensitivity to the influence of wind, dependent on their positioning and different exposure to airflow.

Index Terms—Air quality monitoring, particulate matter, low-cost sensors, laboratory characterization, apparent wind

I. INTRODUCTION

Particulate matter (PM) is a complex mixture of tiny particles and droplets suspended in the air. These particles, varying in size, composition, and origin, can profoundly affect the environment and human health. In fact, the smaller the particles, the deeper they can penetrate the respiratory system and even enter the bloodstream, causing cardiovascular, respiratory, and other health issues [1]. In addition, PM can affect environmental elements such as visibility, ecosystems, and climate change [2]. PM is classified by size, and special interest is raised by $PM_{2.5}$ and PM_{10} [3], particles that have a maximum diameter of $2.5\ \mu\text{m}$ and $10\ \mu\text{m}$, respectively.

Governments and local institutions often use high-quality fixed stations to provide accurate and reliable data on PM concentration [4]. These stations can detect a wide range of pollutants with high accuracy and are essential for regulatory compliance and long-term environmental monitoring.

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However, their high cost and maintenance requirements limit their widespread deployment, leading to gaps in spatial coverage [5].

Low-cost sensors have emerged as a popular alternative to expand air quality monitoring networks [6]. These sensors are affordable, portable, and easy to install, allowing for denser sensor networks and community-based monitoring initiatives. Although they enable broader spatial coverage, typically low-cost sensors have accuracy lower than high-grade monitoring systems, are susceptible to environmental factors, such as humidity and temperature, and often require calibration and data correction algorithms [7]. However, the possibility to increase spatial resolution in air quality monitoring makes it worth designing appropriately networks of low-cost PM sensors over specific geographic areas. PM concentration can indeed differ significantly within distances of the order of tens and hundreds of meters due to traffic, industrial activities, natural sources, and high spatial resolution is crucial to understanding these local variations.

Mobile architectures for air quality monitoring involve mounting sensors on moving platforms such as private vehicles and drones [8] or public transportation systems such as buses and taxis [9]. This approach can significantly enhance spatial resolution and data collection efficiency. Mobile sensors can cover larger areas, track pollution sources, and provide real-time data for dynamic air quality mapping. However, it is essential to address challenges such as ensuring data quality, calibration, and seamless integration with existing fixed monitoring networks. Various techniques, including laboratory characterization before field installation or the possibility of on-the-fly calibration solutions, should be carefully considered [5], [10].

In the context of outdoor monitoring, wind speed plays a critical role, as it can affect the operation of the sensor by changing the airflows at its inlet and outlet. Previous works considered low-cost PM sensors in low-speed wind conditions,

especially addressing indoor environment monitoring. In [11] a wind tunnel with an operating speed not higher than 0.5 m/s was designed to test sensors in an environment with uniform distributed aerosols. No correlation between PM measurements and incident airflow was found, but the impressed wind speed was extremely low and possible problems caused by the presence of larger airflow variations were not excluded. Both on-field and laboratory conditions were considered in [12], where low-cost PM sensors were tested in winter ambient conditions and in a wind tunnel with 0.5 m/s speed. The sensor performance was quantified with and without protective housing, revealing distinctive effects during wind tunnel tests, therefore indicating an airflow influence depending on whether sensors are shielded or wind-exposed. Although in [11] and [12] windy conditions were considered, it is worth highlighting that the focus was not explicitly on detecting specific behaviors caused by wind influence.

In [13] the problem of wind on low-cost sensors PM measurements was explicitly addressed, considering Alphasense OPC N2 and Nova Fitness SDS011 sensor models. Wind speed and direction were monitored using a portable weather station across different outdoor pollution scenarios. The recorded data consistently indicated low wind speeds, predominantly below 1 m/s, with occasional spikes that reached 3 m/s. Therefore, low wind speeds were considered, and in these conditions no discernible relationship was found between PM measurements and wind.

An additional challenge encountered in mobile monitoring applications is the presence of apparent wind, which refers to the wind perceived by a moving observer. Apparent wind poses a potential threat in PM monitoring, as it can alter pollutant concentrations or affect the sensor's fan speed, consequently impacting the readings of mobile sensors and leading to a degradation in the quality of the data reported. As an example, [8] presents a study on the installation of low-cost PM monitoring sensors in drones. The authors were concerned with mitigating the strong influence of the apparent wind on the drone. They achieved this by redesigning the sensors and relocating them to minimize exposure to the airflow generated by the drone motion.

In this context, this study investigates the effects of apparent wind on the estimation of $PM_{2.5}$ by three models of low-cost PM sensors within a laboratory setting. Due to the lack of specific studies on this topic, here this issue is addressed explicitly by setting up a specific test configuration to quantitatively assess the consequences of this influence factor on sensor measurements. To quantify accurately the impact of apparent wind, its influence is intentionally isolated from other ambient parameters, such as temperature and humidity. In the following sections, the test setup and results will be described and discussed.

II. LABORATORY TEST SETUP

The designed test setup aims at replicating, under controlled conditions, the dynamics of a generic urban monitoring scenario, depicted in Fig. 1. There, a fixed high-accuracy

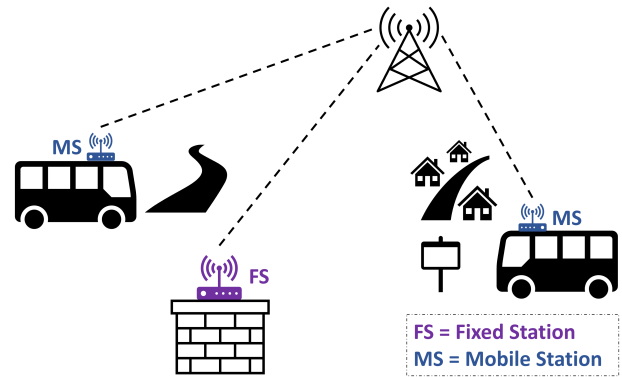


Fig. 1. Urban air quality monitoring scenario.

reference station coexists with public vehicles equipped with mobile PM monitoring stations. Data collected by all devices are typically sent to a central unit in charge of correlating and analyzing the PM measurements [5].

Under windless conditions, only the effect of the apparent wind that the bus encounters during the route as it travels through the urban environment is to be evaluated. Specifically, the intent is to assess the effect of the presence of apparent wind between two bus stops.

Fig. 2 illustrates the laboratory test setup developed to evaluate the performance of low-cost PM sensors under apparent wind influence. The complete experimental setup was designed to mimic real-world conditions in which low-cost PM sensors might be used, ensuring that the results are applicable to real-world air quality monitoring scenarios.

The experimental tests were carried out at the Instrumentation and Measurement Laboratory of the University of Cagliari, Italy, under controlled temperature and humidity conditions, in order to minimize the variability of these factors and focus only on the influence of the apparent wind. This was made to identify the effect of the wind on PM sensor output data. In particular, this study considers the worst case of the sensor without a chassis or specific cover.

Three models of low-cost PM sensors were considered: the

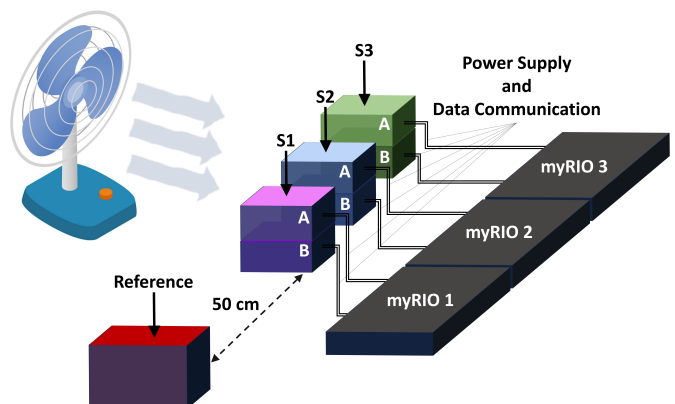


Fig. 2. Laboratory test configuration.

TABLE I
MAIN SPECIFICATIONS OF THE THREE SENSOR MODELS UNDER TEST

Parameter	Sensor		
	S1	S2	S3
PM _{2.5} Concentration Range [$\mu\text{g}/\text{m}^3$]	0 to 1000	0 to 1000	0 to 999
PM _{2.5} Accuracy Range I [$\mu\text{g}/\text{m}^3$] Range II [%]	$\pm 15@[0-100]$ ± 15	$\pm 10@[0-100]$ ± 10	$\pm 10@[0-67]$ ± 15
Operating Temperature Range [$^{\circ}\text{C}$]	-20 to +50	-10 to +60	-10 to +50
Operating Humidity Range [%RH]	0 to 95	0 to 99	0 to 70
Response Time [s]	< 6	< 10	< 10
Air Inlet and Outlet Position	Opposite Sides	Same Side	Opposite Sides

Honeywell HPMA115S0-XXX [14], the Plantower PMS5003 [15] and the Nova Fitness SDS011 [16], in what follows referred to as S1, S2, and S3, respectively. Their main specifications are summarized in Table I. This sensor selection, coming from different manufacturers, is deliberate to investigate the varied behaviors dependent on their construction characteristics. They are in the same price range and their measurement accuracy level is comparable, as it is in the 10 – 15 % range in highly polluted conditions, and they need to be calibrated after leaving the factory. The three considered models base their working principle on the light scattering phenomenon, which exploits the interaction of particles with light to estimate PM concentration in the air. Light scattering takes place in an internal camera, where particles are conveyed from outside leveraging the air pressure difference at the inlet, and they are then pushed out by a fan mounted in proximity of the outlet.

The air inlet and outlet placements on the sensor surface are crucial in windy conditions, as they can influence the air path within the sensor camera as well as the air pressure in the different volumes. Focusing on the sensor models under test, S1 and S3 have their air inlet and outlet in opposite sides, while in S2 they are located on the same side.

For each model, a pair of sensors was used (sensors A and B in Fig. 2), in line with the growing trend of using two identical sensors at PM monitoring stations to enhance data collection redundancy and improve the reliability of the measurement process [17].

Sensor measurements were compared with the TSI DustTrak II Aerosol Monitor, which is commonly used as a reference station in virtue of its high performance. Tests were carried out in a 40 m² laboratory room; therefore, reference station measurements can be considered representative of the actual PM concentration in the whole environment.

A pair of sensors of each model was connected to a National Instruments myRIO-1900 device (from now on myRIO),

which served as a data acquisition platform. Each myRIO platform includes real-time processor, field-programmable gate array (FPGA), analog and digital I/O, voltage regulator, and wireless communication capabilities, making it suitable for reliable and flexible data acquisition.

Power supply was provided to each sensor by the myRIOs, capable of ensuring a 5 V output through their dedicated supply pins. Data communication between sensors and myRIOs was carried out by means of the UART protocol, and PM measurements, time-tagged by the myRIO with a reporting interval of 1 s, were then forwarded to a desktop computer for measurement collection and analysis.

A commercial fan was used to generate a wind flow comparable to the apparent wind on a mobile station installed in a public transportation unit. For this purpose, the fan and sensors positions were adjusted to obtain a 10 ± 1 km/h wind speed in the proximity of all the devices under test. Such speed, which was monitored by a commercial anemometer with a 5 % accuracy, is comparable to the average speed of the public transportation system in the metropolitan area of Cagliari, Italy, equal to 16 km/h [18]. The reference station position was carefully chosen to prevent it from being affected by wind influence, as it was employed as a fixed monitoring unit, unaffected by the apparent wind.

III. RESULTS

This section examines the outcomes of the experiments conducted under the influence of apparent wind. Only PM_{2.5} results are reported, but sensors are also capable of measuring PM₁₀ concentrations. PM_{2.5} concentration has been raised to a 300 $\mu\text{g}/\text{m}^3$ level by the lighting of incense sticks, typically used in scientific literature as pollution sources [13], [19].

Tests were conducted considering only on/off states of the imprinted wind, with the aim of obtaining a clear feedback on the possible dependence of sensor measurements on the influence of apparent wind at a speed appropriate for the considered bus movement. As for the wind application, tests were designed with 5-minutes on and off time intervals, to simulate the possible movement of a city bus on its route between two bus stops. In each test, wind was applied to sensors twice, and the sensors A and B of each model, placed on top of each other to reduce the space variability, were swapped between the two turn-on intervals in order to investigate any changes in behavior due to the different positioning.

Different tests were carried out to investigate the diverse behavior of the sensors depending on their air inlet and outlet positioning with respect to the wind direction, and also by changing the position of the sensors within the test setup. Here, two different tests that can be considered representative of the entire measurement campaign are reported.

In the first test, the sensors air inlets were oriented towards the fan, while in the second one, the wind was imprinted in the direction of the outlets. Data were processed by computing the moving average over 1-minute portions to minimize spikes in measurements due to sensor variability. This causes the

absence of reasonable data in the first minute, as the moving average pre-loading introduces a 1-minute transient to be discarded in data analysis.

A calibration process was performed on sensors data in order to reset their factory offset with respect to the high-accuracy station reference values. This was done to make it possible to perform direct reasoning on sensor accuracy degradation in the presence of the wind influence. Low-cost sensor measurements can be affected, indeed, by high offsets that may vary between different production lots, therefore laboratory calibration is strongly recommended [20]. The indoor experimental conditions and the low duration of the test made it possible to obtain a substantial stationarity of the PM concentration, and this allowed to implement a simple calibration procedure, where sensor measurement offsets were just compensated with respect to the fixed station reference values. For each test, the compensation values were determined as the mean offset between sensor readings and reference station measurements over the initial 2.5 minutes of the test duration, when there was no wind. Given the similarity in offsets observed between the two tests, only the results from the inlet-directed wind test are presented for brevity and they are deemed to be representative.

Table II shows the original (out-of-factory) offsets for each sensor, reported in percentage of the reference values. All sensors considered in this study underestimate the actual PM concentration as it is indicated by the all-negative values. Before the compensation, experimental results show that S2 is the most accurate sensor model, as its offsets are lower than 10 %, already complying with the $\pm 10\%$ accuracy range declared in the sensor data-sheet. S1 and S3 are characterized by higher offsets, with values of about 70 % in the case of S1 and exceeding 80 % in the case of S3. These results highlight the importance of the laboratory sensor calibration, especially if they are fresh out of the factory.

Table II also reports the standard deviation values, evaluated again in percentage of the reference measurements. Such values are to be understood as representative of the sensor measurement precision (i.e. agreement among measured values obtained by repeated measurements). All sensors are characterized by low standard deviations, since in the case of S1 and S3 values do not exceed the 1 % limit, while, even if S2 behaves slightly worse, its values are still around 2 %.

TABLE II
OUT-OF-FACTORY SENSOR MEASUREMENT OFFSETS AND STANDARD DEVIATIONS EVALUATED WITH NO APPARENT WIND (INLET-DIRECTED WIND TEST, $T_{OFF,1}$).

PM _{2.5} concentration offset vs reference and standard deviation						
	S1-A	S1-B	S2-A	S2-B	S3-A	S3-B
Offset [%]	-69.9	-70.0	-1.7	-6.7	-81.5	-82.6
Standard deviation [%]	0.8	0.8	2.2	1.8	0.3	0.5

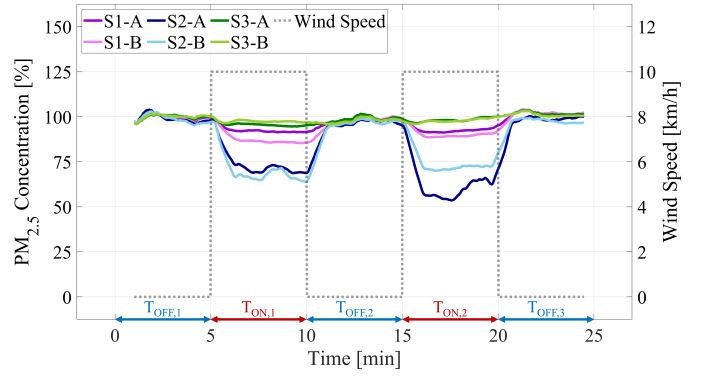


Fig. 3. Time trend of compensated and normalized PM_{2.5} concentration measurements during the inlet-directed wind test.

TABLE III
MEAN VALUES OF SENSOR MEASUREMENTS IN THE FIVE DIFFERENT TIME PORTIONS OF THE INLET-DIRECTED WIND TEST.

PM _{2.5} concentration mean values [% of the reference]					
Sensor	Time portion				
	T _{OFF,1}	T _{ON,1}	T _{OFF,2}	T _{ON,2}	T _{OFF,3}
S1-A	98.9	92.1	98.2	92.8	101.4
S1-B	98.9	86.7	98.1	90.2	102.1
S2-A	97.0	72.5	94.1	61.9	98.6
S2-B	96.4	68.8	95.4	73.7	97.7
S3-A	99.4	95.5	98.6	98.6	101.8
S3-B	99.6	97.3	97.7	98.3	101.2

Considering the out-of-factory conditions, S2 appears the most accurate but least precise sensor, while S1 and S3 stand out in precision rather than accuracy. After the compensation process all sensor models are, in absence of the wind influence, within their accuracy specifications.

A. Inlet-directed Wind Test

Time trends of compensated and normalized (with respect to reference values) PM measurements in the inlet-directed wind test are displayed in Fig. 3. Five different time portions can be discriminated depending on the presence or absence of wind. The fan was turned on in two time intervals of five minutes each, specifically between minutes 5 and 10 ($T_{ON,1}$) and between minutes 15 and 20 ($T_{ON,2}$) of the test. Outside these intervals the fan was kept off, and sensors worked without any airflow influence.

To quantify better the impact of apparent wind, Table III reports the mean values of PM concentration, expressed in percentage of the reference measurements, within each of the five time portions.

The three sensor models, as it is possible to see in Fig. 3, respond differently to the wind influence. S1 and S2 react by

significantly underestimating the PM concentration, while S3 appears to be less sensitive. Measurement variations, which in a first approximation manifest themselves as constant negative offsets with respect to the nominal values, occur immediately after the fan is switched on, confirming the causal relationship between the two events. In the case of S2 sensors, which are the most wind-influenced, estimates are also sensitive to the different exposure of the devices to the fan action, since higher variations were recorded by the sensor placed on the top (see Fig. 2). Indeed, considering the mean values reported in Table III, during the $T_{ON,1}$ interval, in which S2-B is above S2-A, the former underestimates the PM concentration down to the 68.8% of the reference value, while the latter reports a higher value of 72.5%. During the $T_{ON,2}$ interval, after the swap, S2-A measures a mean value of PM concentration of 61.9% of the reference, while S2-B records a higher value of 73.7%. Also S1 sensors are influenced by the wind action, as they are characterized by noticeable variations in their measurements, with mean values ranging from 92.8% to 86.7%. No major wind effects are found on S3 estimates, where, only in $T_{ON,1}$ interval, a slight variation was detected, with mean values of 95.5% and 97.3% for S3-A and S3-B, respectively.

With reference to the experimental standard deviations reported in Table II, it can be stated that wind influence is a threat in the case of S1 and S2 sensors, as the resulting accuracy degradation is one order of magnitude higher than the intrinsic variability of the sensor measurements, while S3 model has proven to be the most immune to the airflow incidence.

These results were obtained using the configuration depicted in Fig. 2, where S1, S2, and S3 were placed from left to right, respectively. As mentioned above, measurements were also obtained by switching sensor positions in different configurations. All the tests performed during the measurement campaign confirmed the intrinsic behavior of the devices, where S2 records the strongest variations, S1 is less influenced, and S3 is essentially immune to the considered wind speed.

B. Outlet-directed Wind Test

Figure 4 illustrates the time trend of PM measurements in the outlet-directed wind test. As with the inlet-directed test, the analysis was done on compensated and normalized measurements with respect to the reference values. Once again, the two conditions of absence and presence of wind were alternated by considering single time intervals of five minutes. A total of five time portions can be distinguished, in which the wind was thus applied twice.

Figure 4 shows that, when the apparent wind blows the air outlet of the sensors, S1 responses are different from that obtained in the previous case-study, as their variations are minimal, while S3 is again not significantly influenced. In the case of S2, the responses are similar, because, given that the air inlet and outlet are located on the same side of the sensor, their orientations were not changed. The average values of the

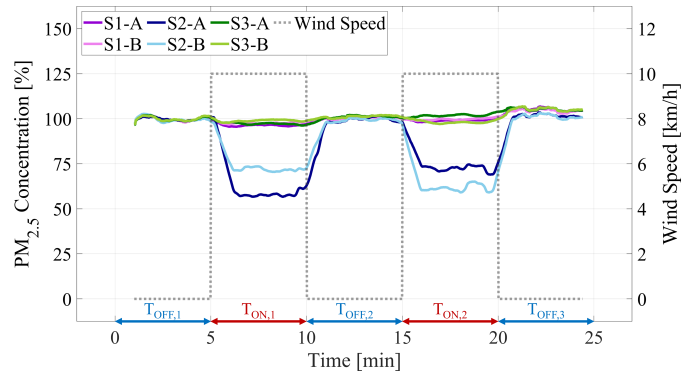


Fig. 4. Time trend of compensated and normalized $PM_{2.5}$ concentration measurements during the outlet-directed wind test.

TABLE IV
MEAN VALUES OF SENSOR MEASUREMENTS IN THE FIVE DIFFERENT TIME PORTIONS OF THE OUTLET-DIRECTED WIND TEST.

PM _{2.5} concentration mean values [% of the reference]					
Sensor	Time portion				
	T _{OFF,1}	T _{ON,1}	T _{OFF,2}	T _{ON,2}	T _{OFF,3}
S1-A	99.5	96.6	100.7	99.4	105.4
S1-B	99.6	97.9	100.1	100.0	104.4
S2-A	97.8	61.4	97.8	73.9	101.5
S2-B	97.7	73.8	96.6	63.9	100.9
S3-A	99.7	97.3	101.1	102.3	105.3
S3-B	99.8	99.1	101.1	98.4	105.3

PM measurements, calculated over the individual intervals and expressed in percentage terms, are reported in Table IV.

Numerical results confirm what is observed from the time trend in Fig. 4, with S2 sensors being the only ones recording noticeable measurement variations due to the wind presence (in this case, unlike the inlet-directed test presented in Section III-A, during the first wind application the A-sensors were placed on top of the B-sensors). The outcomes obtained in the wind application intervals, as expected from the identical configuration, are in line with the previous test, with $PM_{2.5}$ concentration estimates dropping between the 61.4% and 73.9% of the reference values. The wide width of this range is due to the different response of the sensors when placed above or below each other, as noticed in the inlet-directed test. Again, a greater impact of wind on the sensor positioned above is confirmed, with a difference on the mean of the estimates exceeding the 10% between the two devices. In the case of S1 and S3, a trend on $PM_{2.5}$ measurements correlated with wind variation is not well discernible, as the mean decreases do not exceed 4% in either sensor in the two different wind applications. These variations are of the same order of magnitude as the experimental standard deviations reported for

the six sensors in Table II, so it cannot be concluded that they are due to the effect of wind.

IV. CONCLUSIONS

Affordable PM sensors are increasingly used for monitoring urban air quality due to their simplicity and economical cost, with the aim of enhancing spatial resolution. When considering mobile monitoring stations, they are mounted on vehicles and apparent wind can be a potential source of uncertainty in the collected measurements. In this paper, the effects of apparent wind on three different low-cost sensor models were investigated by replicating, in a laboratory setting, realistic conditions experienced by a vehicle moving in an urban context. Sensors exhibited different responses to apparent wind presence, as two out of three models showed significant variations in their PM_{2.5} measurements (up to -30%, considering average underestimation). Sensor measurement variations due to the wind impact were found to be considerably higher than experimental sensor uncertainty, evaluated in terms of standard deviation of measurements in steady-state conditions. Furthermore, different responses were observed depending on the wind direction with respect to the air inlet and outlet of the sensors, suggesting that an accurate choice of sensor model and a careful evaluation of the placement of devices in a mobile monitoring scenario, such as city buses, should be made. Results prove the importance of considering the apparent wind in the set of the possible influence factors in the scenario of mobile PM monitoring applications, and pave the way for the development of model-specific compensation procedures.

REFERENCES

- [1] D. Merkl, M. KrauBe, and M. F. Wagner, "The Underestimated Influence of Air Quality - Implementing a Homogenous Network Structure for an IoT-Based Data Acquisition and Analysis System," in *2022 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT)*, Jun. 2022, pp. 343–348.
- [2] H. Zhou, J. He, B. Zhao, L. Zhang, Q. Fan, C. Lü, Dudagula, T. Liu, and Y. Yuan, "The distribution of PM10 and PM2.5 carbonaceous aerosol in Baotou, China," *Atmospheric Research*, vol. 178–179, pp. 102–113, Sep. 2016.
- [3] H. Mei, P. Han, Y. Wang, N. Zeng, D. Liu, Q. Cai, Z. Deng, Y. Wang, Y. Pan, and X. Tang, "Field Evaluation of Low-Cost Particulate Matter Sensors in Beijing," *Sensors*, vol. 20, no. 16, p. 4381, Jan. 2020.
- [4] D. Suriano and M. Prato, "An Investigation on the Possible Application Areas of Low-Cost PM Sensors for Air Quality Monitoring," *Sensors*, vol. 23, no. 8, p. 3976, Jan. 2023.
- [5] P. Castello, C. Muscas, P. A. Pegoraro, and S. Sulis, "Improved Fine Particles Monitoring in Smart Cities by Means of Advanced Data Concentrator," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–9, 2021.
- [6] B. Alfano, L. Barretta, A. Del Giudice, S. De Vito, G. Di Francia, E. Esposito, F. Formisano, E. Massera, M. L. Miglietta, and T. Polichetti, "A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives," *Sensors*, vol. 20, no. 23, p. 6819, Jan. 2020.
- [7] T. Zheng, M. H. Bergin, K. K. Johnson, S. N. Tripathi, S. Shirodkar, M. S. Landis, R. Sutaria, and D. E. Carlson, "Field evaluation of low-cost particulate matter sensors in high- and low-concentration environments," *Atmospheric Measurement Techniques*, vol. 11, no. 8, pp. 4823–4846, Aug. 2018.
- [8] G. M. Bolla, M. Casagrande, A. Comazzetto, R. Dal Moro, M. Destro, E. Fantin, G. Colombatti, A. Aboudan, and E. C. Lorenzini, "ARIA: Air Pollutants Monitoring Using UAVs," in *2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, Jun. 2018, pp. 225–229.
- [9] H. Zarrar and V. Dyo, "Drive-by Air Pollution Sensing Systems: Challenges and Future Directions," *IEEE Sensors Journal*, vol. 23, no. 19, pp. 23 692–23 703, Oct. 2023.
- [10] Y. Wang, J. Li, H. Jing, Q. Zhang, J. Jiang, and P. Biswas, "Laboratory Evaluation and Calibration of Three Low-Cost Particle Sensors for Particulate Matter Measurement," *Aerosol Science and Technology*, vol. 49, no. 11, pp. 1063–1077, Nov. 2015.
- [11] R. J. Vercellino, D. K. Sleeth, R. G. Handy, K. T. Min, and S. C. Collingwood, "Laboratory Evaluation of a Low-cost, Real-time, Aerosol Multi-Sensor," *Journal of occupational and environmental hygiene*, vol. 15, no. 7, pp. 559–567, Jul. 2018.
- [12] K. E. Kelly, J. Whitaker, A. Petty, C. Widmer, A. Dybwad, D. Sleeth, R. Martin, and A. Butterfield, "Ambient and laboratory evaluation of a low-cost particulate matter sensor," *Environmental Pollution*, vol. 221, pp. 491–500, Feb. 2017.
- [13] R. Dubey, A. K. Patra, J. Joshi, D. Blankenberg, S. S. R. Kolluru, B. Madhu, and S. Raval, "Evaluation of low-cost particulate matter sensors OPC N2 and PM Nova for aerosol monitoring," *Atmospheric Pollution Research*, vol. 13, no. 3, p. 101335, Mar. 2022.
- [14] "HPM Series Particulate Matter Sensors | Honeywell." [Online]. Available: <https://sps.honeywell.com/us/en/products/advanced-sensing-technologies/healthcare-sensing/particulate-matter-sensors/hpm-series>
- [15] "PMS5003 – Laser PM2.5 Sensor-Plantower Technology." [Online]. Available: https://www.plantower.com/en/products_33/74.html
- [16] "SDS011 Dust sensor-atmospheric environment-Shandong Nova." [Online]. Available: http://en.novasensor.cn/?list_13/55.html
- [17] I. Stavroulas, G. Grivas, P. Michalopoulos, E. Liakakou, A. Bougiatioti, P. Kalkavouras, K. M. Fameli, N. Hatzianastassiou, N. Mihalopoulos, and E. Gerasopoulos, "Field Evaluation of Low-Cost PM Sensors (Purple Air PA-II) Under Variable Urban Air Quality Conditions, in Greece," *Atmosphere*, vol. 11, no. 9, p. 926, Sep. 2020.
- [18] "CTM - Carta della Mobilità 2023-2024." [Online]. Available: <https://ctmcagliari.portaletrasparenza.net/it/trasparenza/servizi-erogati/carta-dei-servizi-e-standard-di-qualita.html>
- [19] S. C. Lung, M. M. Tsou, S. Hu, Y. Hsieh, W. V. Wang, C. Shui, and C. Tan, "Concurrent assessment of personal, indoor, and outdoor PM2.5 and PM1 levels and source contributions using novel low-cost sensing devices," *Indoor Air*, vol. 31, no. 3, pp. 755–768, May 2021.
- [20] N. Castell, F. R. Dauge, P. Schneider, M. Vogt, U. Lerner, B. Fishbain, D. Broday, and A. Bartonova, "Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?" *Environment International*, vol. 99, pp. 293–302, Feb. 2017.