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ORIGINAL

Effects of Vehicular Congestion on Air Quality in High-Altitude Cities: Case Study of Ibarra, Ecuador

Efectos de la Congestión Vehicular en la Calidad del Aire en Ciudades de altura. Estudio de Caso: Ibarra, Ecuador

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ABSTRACT

Air pollution, primarily driven by vehicular emissions, is a growing challenge in Latin American cities. In Ibarra, Ecuador, the lack of air quality records prompted the implementation of a low-cost monitoring system. In this study, one AirGradient O-1PST sensor were installed near the Amazonas central market, a zone characterized by heavy traffic, where $PM_{2,5}$, PM_{10}, and CO_2 concentrations were measured over seven consecutive days. Results showed that PM_{10} daily concentrations remained below the limits established by national regulations, whereas $PM_{2,5}$ levels exceeded the World Health Organization (WHO) recommendations most of the days, reaching an average of approximately 0,019 mg/m³. The reliability of the AirGradient O-1PST sensor was validated through comparison with a reference-grade instrument (Thermo Andersen FH62C14), revealing a strong correlation, with a coefficient of determination close to 95 % for daily $PM_{2,5}$ averages. Additionally, a direct association was found between vehicular traffic density and the concentrations of both air pollutants and greenhouse gases, particularly during peak hours. The findings demonstrate that, when properly validated, low-cost sensors are effective tools for air quality assessment in urban areas, and they can serve as a valuable complement to official monitoring networks. This study contributes to promoting the adoption of accessible environmental surveillance technologies in intermediate Latin American cities, thereby supporting informed decision-making in public health, sustainable urban planning, and transport management.

Keywords: Low-Cost Sensors; Air Quality; Vehicular Emissions; Particulate Matter; Intermediate Cities.

RESUMEN

La contaminación del aire, impulsada por las emisiones vehiculares, representa un desafío para las ciudades latinoamericanas. En Ibarra, Ecuador, la ausencia de registros actuales sobre calidad del aire motivó la implementación de un sistema de monitoreo de bajo costo. En este estudio, se instaló un sensor AirGradient O-1PST en las inmediaciones del mercado central Amazonas, zona caracterizada por un tráfico vehicular, donde se midió las concentraciones de $PM_{2,5}$, PM_{10} y CO_2 durante siete días consecutivos. Los resultados mostraron que las concentraciones diarias de PM_{10} se mantuvieron por debajo de los límites establecidos por la normativa nacional, mientras que los niveles de $PM_{2,5}$ superaron las recomendaciones de la Organización Mundial de la Salud (OMS), alcanzando un promedio de 0,019 mg/m³. La fiabilidad del sensor AirGradient O-1PST fue validada mediante un equipo de referencia (Thermo Andersen FH62C14), revelando una fuerte correlación, con un coeficiente de determinación de 95 % para los promedios diarios de $PM_{2,5}$. Además, se identificó una correlación directa entre la densidad del tráfico y las concentraciones de gases contaminantes y de efecto invernadero, especialmente durante horas pico. Los hallazgos demuestran que, cuando se validan adecuadamente, los sensores de bajo costo son herramientas eficaces para la evaluación de la calidad del aire en zonas urbanas y pueden complementar efectivamente las redes oficiales de monitoreo. Este estudio contribuye a fomentar la adopción de tecnologías accesibles de vigilancia ambiental en ciudades intermedias de América Latina, apoyando la toma de decisiones informadas en salud pública, planificación urbana y gestión del transporte.

Palabras clave: Sensores de Bajo Costo; Calidad del Aire; Emisiones Vehiculares; Material Particulado; Ciudades Intermedias.

INTRODUCTION

Urban air pollution has become a critical threat to environmental sustainability and public health across the globe,[1] contributing to millions of premature deaths each year.[2] Vehicular emissions remain one of the most pervasive sources of atmospheric pollution in cities,[3] releasing pollutants such as particulate matter (PM_{10} and $PM_{2,5}$), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and hydrocarbons (HC).[4] These substances are directly linked to respiratory infections, cardiovascular diseases, and increased risk of mortality due to long-term exposure.[5] In Latin America, nearly 40 % of cities exceed the World Health Organization (WHO) guidelines for $PM_{2,5}$, and over 85 % of the urban population is exposed to NO_2 concentrations above recommended thresholds.[6]

Traffic congestion is a dominant factor exacerbating urban air pollution. Stop-and-go driving, idling, and frequent acceleration common in congested roads lead to higher emissions of CO, NO_2, and PM_{10}.[7] Cities such as Bogotá, Mexico City, and Santiago frequently rank among the most congested in the world,[2] and studies have shown a strong correlation between traffic density and elevated NO_2 levels. In Ecuador, the land transport sector accounted for 19427,6 kt of CO_2 eq in 2022, according to national inventories reported under IPCC guidelines.[8]

Monitoring air quality is essential to inform effective urban planning and regulatory policies.[9] However, conventional monitoring systems—based on reference-grade instruments—require substantial investment and technical capacity, limiting their implementation in many intermediate cities in Latin America.[10] This lack of infrastructure has contributed to the scarcity of continuous, real-time air quality data, particularly in high-altitude Andean development cities where the behavior of emissions is influenced by geographic and climatic variables.[11] At higher altitudes, lower atmospheric pressure and oxygen levels alter engine combustion efficiency,[12] leading to increases in NO¤, CO, and PM emissions.[13] In Ecuador, fuel quality restrictions—such as high sulfur content—have limited the adoption of advanced emission control technologies, with vehicle homologation constrained to Euro II standards for heavy-duty vehicles and Euro 3 for light-duty vehicles.[14,15]

In recent years, low-cost sensors (LCS) have emerged as a viable alternative to traditional air quality monitoring infrastructure.[9] These devices offer affordable, real-time, and spatially distributed data, and have been successfully deployed in cities worldwide for the measurement of $PM_{2,5}$, CO_2, and other pollutants.[3] When properly calibrated and validated, LCS can complement existing networks and help bridge data gaps in under-monitored areas.[16]

This study was performed in Ibarra, Ecuador, a mid-sized Andean city located at 2 200 meters above sea level, with an estimated population of 221 000 inhabitants.[17] On 2024, a total of 89 718 vehicles were registered on Ibarra's municipal traffic agency,[18] raising concerns about local air quality and congestion. Despite this, no formal monitoring has been conducted in the city since 2015,[19] and critical urban zones such as the Amazonas market area—characterized by high vehicle density and commercial activity—remain unmonitored.

To address these gaps, this research integrates low-cost air quality sensors and urban mobility analysis to produce new scientific evidence. Specifically, the two main contributions are: the provision of empirical real-time data on $PM_{2,5}$, PM_{10}, and CO_2 concentrations in a high-altitude intermediate city; and the validation of the performance of AirGradient O-1PST low-cost sensors by comparison with reference-grade equipment under altitude-specific conditions. Combining LCS, air quality standards, and local traffic conditions, this study offers a replicable framework for development cities and other resource-constrained urban areas. Its findings support the implementation of scalable and accessible monitoring strategies using LCS to strengthen environmental policy, public health planning, and urban sustainability.

The findings reveal that low-cost sensors exhibited strong correlation with reference equipment for daily average $PM_{2,5}$ concentrations, indicating their suitability for long-term air quality assessments. A strong relationship was found between $PM_{2,5}$ levels and vehicular traffic intensity, particularly during peak congestion periods. Furthermore, $PM_{2,5}$ concentrations frequently exceeded WHO recommended limits, especially at densely trafficked zones. These results underscore the utility of low-cost sensors for identifying urban pollution patterns in intermediate cities and offer a replicable model for other high-altitude regions facing similar monitoring and public health challenges.

METHOD

This study followed a structured and replicable methodological approach to assess the impact of vehicular congestion on urban air quality using low-cost sensor (LCS) technology. The methodology was divided into four stages: data acquisition, data preprocessing, modeling and validation, and regulatory analysis.

Study Area and Context

The study was conducted in Ibarra, Ecuador, a representative intermediate city located at 2 200 meters above sea level, with an estimated population of 221 000 inhabitants.[17] In particular, in the main city market. Due to the absence of continuous air quality monitoring since 2015, the city presents a critical data gap for effective environmental management. High-altitude cities exhibit unique atmospheric conditions—such as reduced air pressure and oxygen concentration—that affect combustion efficiency and elevate emissions of $PM_{2,5}$, PM_{10}, and CO_2.

Data Acquisition Using Low-Cost Sensors

Two certified AirGradient O-1PST low-cost air quality sensor were installed on-site for continuously recording concentrations of $PM_{2,5}$, PM_{10}, and CO_2 over seven consecutive days, and following the recommendations of the Environmental Protection Agency (EPA) for the installation of air quality monitors. The data acquired each minute allowed for the identification of short-term pollution peaks and trends under real urban driving conditions.

Table 1. Specifications of the AirGradient O-1PST Monitor

Specifications	Description
Model	O-1PST (for outdoor use)
Parameters	PM Sensor (PMS5003T): ±10 %@100 μg/m³ CO_2 Sensor (SenseAir S8): ±40 ppm ±3 % TVOC/NOx Sensor (SGP41): TVOC <±15 @ 0-500, NOx <±50 @ 0-500 Temperature ±0,2 °C (0-70 °C), Humidity ±3,5 % RH (20-80 %)
Connectivity	2,4 GHz Wi-Fi & Bluetoot
Weight	350 g
Certifications	CE, RoHS, REACH, FCC ID: 2AC7Z-ESPC3MINI
Source: [20].	

Vehicle Classification and Manual Traffic Observation

Traffic counts were conducted manually over five business days during peak hours—07:00-09:00 and 17:00-19:00. Vehicles were classified into three categories: light-duty vehicles (Taxis, private cars, small vans, SUV, small trucks), heavy-duty vehicles (Buses, trucks, commercial cargo vehicles), and motorcycles (Two-wheeled motorized vehicles).

Two key indicators were calculated to quantify congestion:

i. Traffic Intensity (Ti), representing the average number of vehicles per hour, calculated as:

$$Ti = \frac{n}{t}$$

where *n* is the total number of vehicles during the time period *t* (in hours).

ii. Peak Hour Factor (PhF), expressing traffic demand concentration during peak periods, was determined by:

$$PhF = \frac{V_{Ph}}{4 \,.\, V_{max}}$$

where V_{Ph} is the total number of vehicles during the peak hour and V_{max} is the maximum volume observed in a 15-minute subinterval. The results for these metrics across different time intervals are summarized in table 2.

Table 2. Traffic Intensity and Peak Hour Factor per Time Interval

Time Interval	Max volme (veh/15 minutes)	Traffic Intensity (Ti) *(veh/h)*	Peak Hour Factor (PhF)
07:00-08:00	130	460,0	0,885
08:00-09:00	145	520,0	0,897
17:00-18:00	170	610,0	0,897
18:00-19:00	160	580,0	0,906

Data Preprocessing and Analysis

Data from the sensor and manual traffic observations were first **cleaned and time-synchronized**. Pollution data were aggregated into standardized time series to facilitate correlation with traffic intensity. Descriptive analyses identified peak pollution periods and daily concentration cycles. Missing data were interpolated using linear regression, and outliers were removed based on the interquartile range (IQR) method.

Statistical Modeling and Sensor Validation

A correlation model was developed to evaluate the association between traffic volume and pollutant concentrations. Pearson correlation coefficients (r) and coefficient of determination (R^2) were calculated to assess the strength and the relationship between observed traffic patterns and pollutant levels.

To assess the accuracy of the low-cost AirGradient monitor, the $PM_{2,5}$. measurements were compared against data from the Belisario reference station. Both datasets were collected during a 15-day period in July 2024, using hourly and daily averages expressed in milligrams per cubic meter (mg/m^3). To assess sensor performance, AirGradient readings were validated against the reference station using linear regression, residual plots, and RMSE (Root Mean Square Error) analysis. This follows best practices from studies evaluating LCS in both developed and developing contexts.[10]

RESULTS

Air Quality trends

The low-cost AirGradient O-1PST sensor recorded $PM_{2,5}$, PM_{10}, and CO_2 concentrations. CO_2 concentrations exhibited a clear diurnal cycle, with values peaking during traffic congestion and declining during off-peak hours. Maximum observed values reached over 600 ppm, which, while not acutely hazardous, signal the role of traffic in contributing to urban greenhouse gases generation.

The data also revealed that PM_{10} concentrations remained below the national threshold established by Ecuadorian environmental regulations[21] (0,050 mg/m^3 for 24-hour average). However, as shown in Figure 1. $PM_{2,5}$ exceeded the WHO guidelines of 0,015 mg/m^3 on several days,[22] with an average daily value of 0,019 mg/m^3 on the monitoring period. This suggests potential health risks in high-exposure zones, particularly during morning and afternoon peak hours.

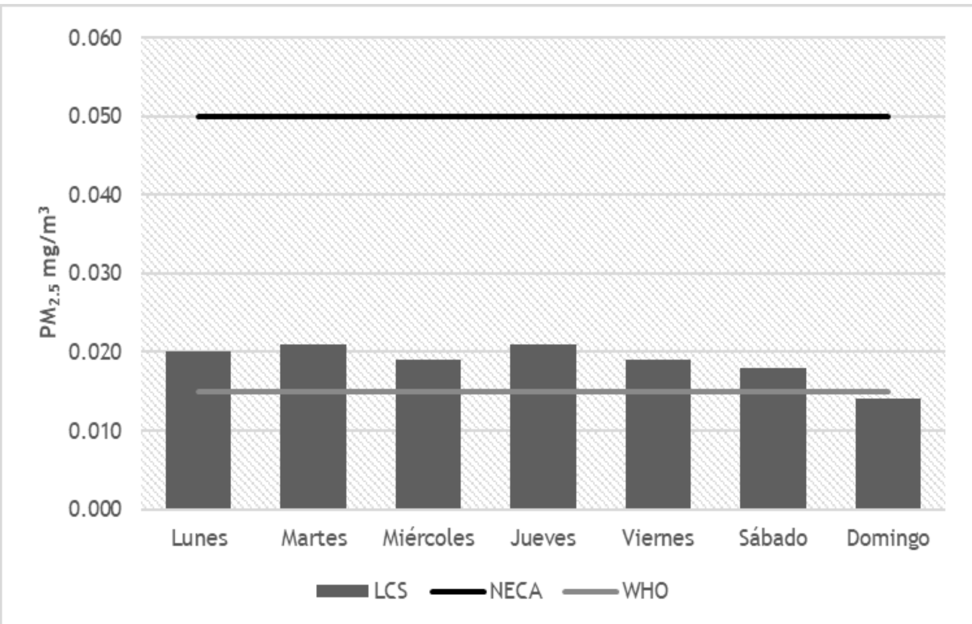

Figure 1. Average $PM_{2,5}$ by Day of Week

Sensor Validation based on Reference Station

The hourly data analysis revealed a moderate correlation between the LCS and the reference station, with a coefficient of determination $R^2 = 0,30$. While the sensor generally measured low concentration values closely, a noticeable dispersion of data points was observed as $PM_{2,5}$ levels increased. This suggests that under higher pollution scenarios, the sensor's readings deviate more significantly from those of the reference monitor. Such variability could pose limitations for detecting acute pollution episodes when relying solely on low-cost technology.

In contrast, the comparison using daily averages showed a strong agreement between the AirGradient and the Belisario station, with an R^2 value of 0,95. In this case, the measurements remained consistently aligned across both low and high concentration ranges, indicating that the low-cost monitor is highly reliable for tracking daily $PM_{2,5}$ trends. These findings highlight a key strength of the AirGradient system: while it may underperform at high temporal resolutions, it proves to be effective for daily monitoring applications, especially in cities with limited access to conventional infrastructure.

In summary, the AirGradient monitor demonstrated strong compatibility with the reference station when daily averages were considered, supporting its suitability for air quality assessments aligned with Ecuadorian air quality regulations, which emphasize daily and annual averages. These results reinforce the potential of low-cost sensors as complementary tools for long-term environmental surveillance in urban areas with budget constraints.

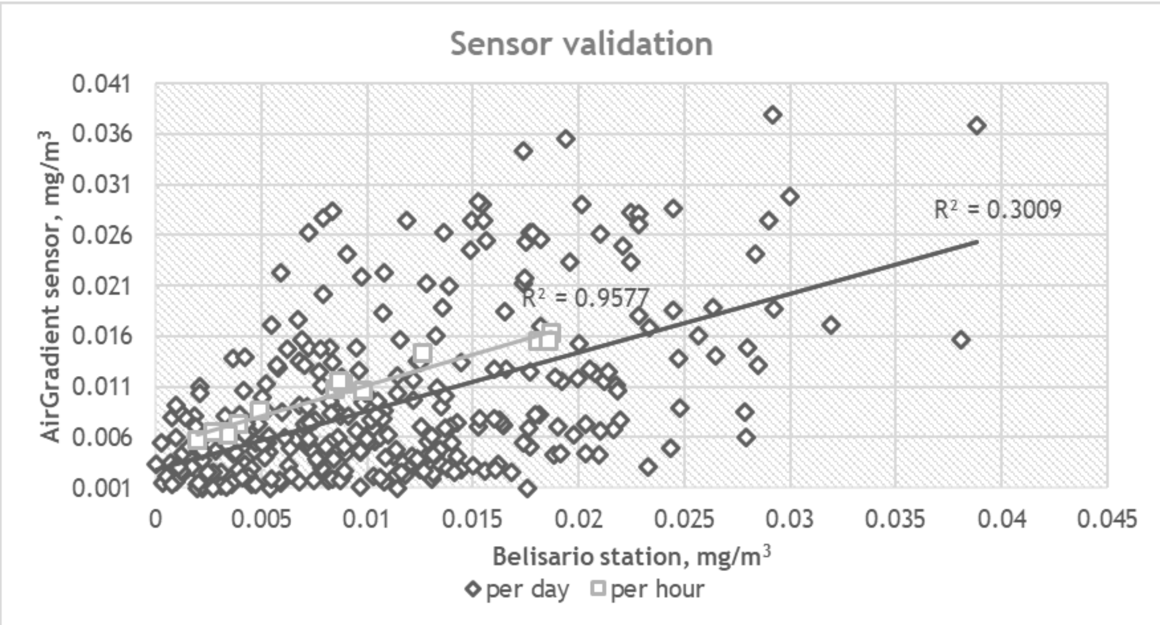

Figure 2. Correlation between Air gradient sensor and reference station

Traffic-Emission Correlation

The study showed that the relationship between traffic volume and pollutant emissions varied significantly depending on the pollutant measured and the temporal resolution of the data. For CO_2, a weak correlation was observed across all timeframes. Hourly averages yielded an R^2 of 0,031, mid-day values improved slightly to 0,386, while daily averages showed the weakest relationship at just 0,012. These low correlations suggest that CO_2 concentrations are influenced by factors beyond vehicular count, such as background atmospheric levels, meteorological conditions, and sensor positioning.

In contrast, $PM_{2,5}$ emissions exhibited a much stronger correlation with traffic volume, especially with heavy-duty vehicle counts. Hourly data produced a moderate R^2 of 0,252, which increased to 0,830 for midday averages and peaked at 0,856 in daily averages. These findings indicate a robust relationship between particulate pollution and vehicle activity, particularly during peak traffic periods. The reliability of the $PM_{2,5}$ sensor further supports the validity of these associations in the monitored urban setting.

Similarly, PM_{10} demonstrated strong correlations, closely mirroring $PM_{2,5}$ behavior. The coefficient increased from 0,240 (hourly) to 0,818 (mid-day) and reached 0,898 for daily averages. These results confirm that particulate emissions are closely tied to vehicular intensity, especially under conditions where dispersion is limited and traffic volume is sustained. Consequently, particulate matter—rather than CO_2—emerges as a more sensitive indicator of short-term urban vehicular pollution.

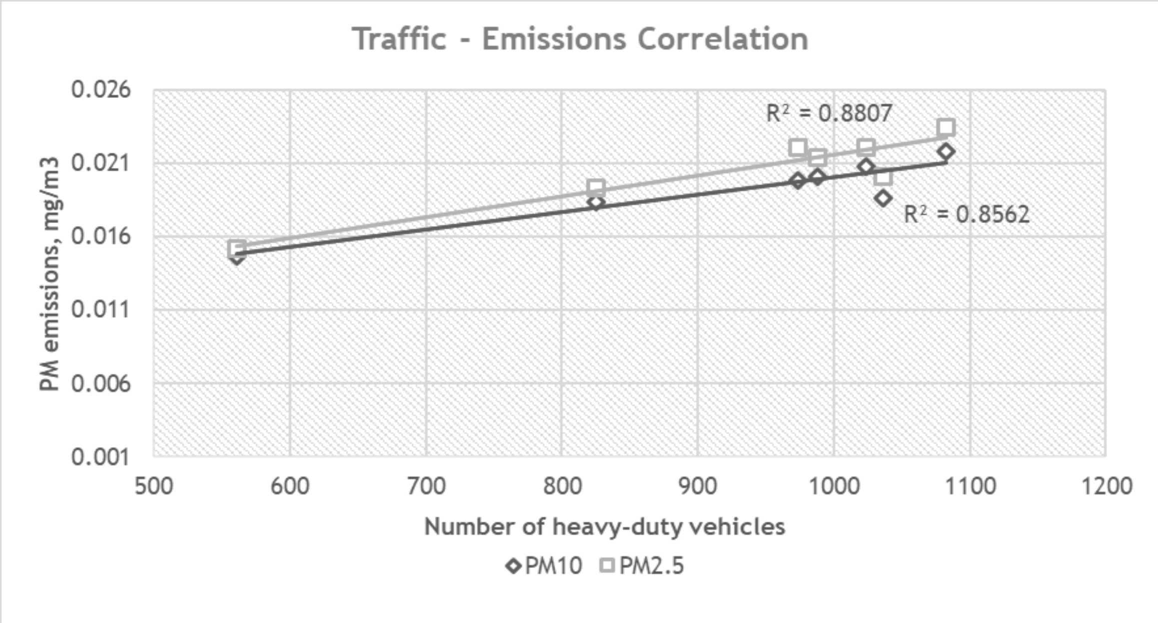

Figure 3. Average daily PM_{10} vs $PM_{2,5}$ emissions

CONCLUSIONS

The AirGradient low-cost sensor demonstrated high reliability for daily average measurements of $PM_{2,5}$ when compared to the approved reference station, achieving a correlation coefficient of $R^2 = 0,95$. However, its performance on hourly scales was notably lower ($R^2 = 0,30$), the suitability of low-cost sensors (LCS) is confirmed primarily for long-term exposure assessments and regulatory monitoring aligned with air quality standards, which are based on daily and annual averaging periods.

The study demonstrates that $PM_{2,5}$ concentrations showed a strong positive correlation with vehicular traffic intensity, particularly with heavy-duty vehicles. This relationship was evident in midday and daily averages, suggesting that traffic emissions are a dominant source of fine particulate pollution in the study area.

Measured $PM_{2,5}$ levels exceeded the World Health Organization recommended daily limit of 0,015 mg/m^3 on multiple days throughout the week. This indicates potential public health risks in densely trafficked urban zones such as Ibarra's commercial corridor, underscoring the urgent need for traffic management strategies and continuous air quality monitoring.

In future work, weather stations could be used to analyze wind direction. Additionally, it would be useful to develop dispersion models to understand the sources and possible effects of air pollutants.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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Methodology: Zamir Mera, Cristian Oto.
Project management: Zamir Mera.
Resources: Ramiro Rosero.
Software: Cristian Oto.
Supervision: Zamir Mera, Ramiro Rosero.
Validation: Cristian Oto, Luis Garzón.
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Writing - proofreading and editing: Ramiro Rosero, Zamir Mera, Luis Garzón.