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A Computationally Implemented Method for Assessing Air Pollution in Urban Traffic Based on Traffic Density Analysis

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Abstract: Monitoring and assessing air pollution levels in urban areas represents a key challenge in environmental protection and traffic management. This paper proposes a computationally implemented method for indirect air pollution assessment based on traffic density analysis, eliminating the need for direct sensor-based measurements of pollutant concentrations. The proposed system employs computer vision for real-time vehicle detection and classification, while air pollution levels are estimated using a mathematical model that accounts for the average emission rates per vehicle. The system architecture includes an embedded computer (Raspberry Pi) for video data processing, network infrastructure connectivity, and data transmission to a central server for further analysis and visualization. Experimental results confirm that the proposed approach enables reliable and efficient air pollution assessment under real-world conditions, opening avenues for enhancing environmental monitoring strategies and optimizing traffic flow in urban environments.

Keywords: Air pollution assessment, traffic analysis, IoT, computer vision, mathematical modeling, urban ecosystems

1 INTRODUCTION

Air pollution is one of the most serious environmental problems today, with a direct impact on human health and the environment. Increased urbanization and intense traffic in cities significantly contribute to higher concentrations of harmful gases, such as carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter PM2.5 and PM10, which negatively affect air quality. Monitoring pollution levels is crucial for implementing effective environmental protection measures and improving the quality of life for citizens.

Numerous studies have highlighted the detrimental effects of air pollution on both human health and the environment. According to Manisalidis et al. (2020), air pollution is a major contributor to respiratory and cardiovascular diseases, reproductive and neurological disorders, and even cancer. Pollutants such as particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and heavy metals have been linked to increased morbidity and mortality rates. The study emphasizes that urbanization and industrial activities significantly contribute to air pollution, exacerbating its harmful effects on public health. Furthermore, climate change, driven in part by air pollution, influences the spread of infectious diseases and intensifies environmental degradation. Addressing this issue requires a multidisciplinary approach, including continuous monitoring, public awareness, and the development of sustainable solutions [1].

Although sensor-based air pollution measurement systems are precise and reliable, they are not available in every part of the city, making continuous and comprehensive air quality monitoring challenging. The limited availability of these sensors can lead to incomplete or inaccurate data, hindering the implementation of adequate measures to reduce pollution. Therefore, it is necessary to develop alternative methods for assessing pollution levels that do not require direct measurement of pollutant concentrations but still provide a reliable estimation of air quality in urban areas.

This paper proposes a novel approach to indirect air pollution assessment using traffic density analysis. By implementing a system that utilizes computer vision for vehicle detection and classification, it is possible to estimate pollution levels based on the average emissions of individual vehicle types. This method enables continuous real-time pollution monitoring without the need to deploy a large number of sensors. The application of this system can enhance environmental protection strategies, enable more accurate pollution assessments, and contribute to optimizing traffic flow in urban areas.

2 RELATED WORK AND COMPARISON

The issue of assessing air pollution in urban environments caused by traffic is attracting increasing attention from researchers, given the significant impact of traffic infrastructure and density on air pollution and public health. Modern studies utilize various approaches, including machine learning, traffic density analysis, and sensor-based models.

The authors of the study [2] propose a method for predicting urban air pollution caused by traffic using data from web applications (Google Traffic). They applied a machine learning approach by training a decision tree algorithm to predict PM2.5 concentration.

On the other hand, the study by Ranka Godec et al. [3] analyzed the impact of traffic density on pollution levels by measuring PM10 particles, carbon (elemental and organic), and polycyclic aromatic hydrocarbons (PAHs), as well as gas pollutants (SO_2, NO_2, and CO) at various intersections. The results indicated significant differences in PM10 concentrations between locations, with the highest values recorded in areas with the densest traffic. Additionally, it was observed that residential heating during nighttime contributes to PAH emissions, highlighting the need for comprehensive models that account for multiple pollution sources.

Kostadinov et al. [4] used recurrent neural networks (RNN) with LSTM units to forecast PM10 levels in Skopje. Their model demonstrated that vehicles are not the primary source of air pollution, emphasizing the need for a holistic approach that considers industrial and climatic factors.

Govea et al. [5] developed a system based on IoT technologies and predictive models, utilizing convolutional neural networks and decision trees for traffic data analysis and PM2.5 and noise mapping. Their model achieved high accuracy (R^2 = 0.93 for PM2.5 and R^2 = 0.90 for noise); however, it depends on the availability of IoT sensors, which can be a limiting factor in certain urban environments.

The study [6] presents findings showing that traffic network parameters, such as traffic density and the number of intersections, significantly correlate with PM2.5 concentrations. This research highlights the necessity of detailed spatial analysis of traffic and air pollution, as correlations identified using the GWR model were significantly more precise than those obtained through standard linear regression analyses.

Mapping urban air quality is widely applied in urban planning; therefore, the authors [7] developed the CLADF (Contextually Localized Adaptive Deep Forest) model for precise mapping of NO_2 pollution with a resolution of 100 m and 1 hour, using mobile sensors and traffic flow as key contextual factors.

Compared to previous research, our method offers an innovative and practical approach to air pollution assessment by analyzing traffic density through computer vision. Unlike methods based on IoT sensors [5] or deep neural networks [4], our system enables autonomous data collection using real-time video analysis, eliminating the need for external data sources and predictions.

Additionally, our approach considers the number of vehicles and their average emissions, allowing for more accurate estimations compared to statistical models such as the one proposed in the study by Ranka Godec et al. [3]. While the GWR-based study [6] provides a detailed analysis of traffic's impact on PM2.5 levels, our method enables direct analysis of real-time traffic conditions and pollution levels, making it more suitable for implementation in urban environments.

3 METHODOLOGY

The proposed method for assessing air pollution in urban areas is based on traffic density analysis using computer vision techniques and a mathematical emission estimation model. This method enables indirect determination of air pollution levels without the need for direct sensors to measure the concentration of harmful gases.

- **Setting up the development environment**

Figure 1 shows the hardware implementation of the system in multiple steps. The hardware foundation consists of an embedded Raspberry Pi computer connected to a surveillance camera placed in a high-traffic location. The camera continuously captures real-time video footage, while the Raspberry Pi processes the recorded material using computer vision algorithms based on the OpenCV library.

- **Vehicle detection and classification**

The video footage is processed in real time, with the system detecting and recognizing vehicles using pre-trained object detection models. A key aspect of this methodology is identifying and counting vehicles that cross a defined observation line, providing data on traffic density within the observed time interval.

- **Data transmission to the central server**

The system records the number of vehicles every two hours and transmits the data to a central server via the internet. The server performs additional data processing using a mathematical model for estimating pollutant emissions. The model takes into account the average emission values of gases such as SO_2, NO_2, O_3, CO, PM10, and PM2.5 per vehicle, which are then multiplied by the number of detected vehicles to obtain the total air pollution level for SO_2, NO_2, O_3, CO, PM10, and PM2.5 during that time period.

The mathematical model is based on the formula Eq(1).

$$P_{XX} = \sum_{i=1}^{N} P_{xx,i} \times N_i \qquad (1)$$

Where:

XX **-** represents any of the present pollutants, such as SO_2, NO_2, O_3, CO, PM10, or PM2.5.

$\mathbf{P_{xx}}$ – estimated emissions of individual pollutants.

$\mathbf{P_{xx,i}}$– average emissions of individual pollutants per vehicle of type i.

$\mathbf{N_i}$ – number of vehicles of type i detected during the observed period.

N – total number of different vehicle types.

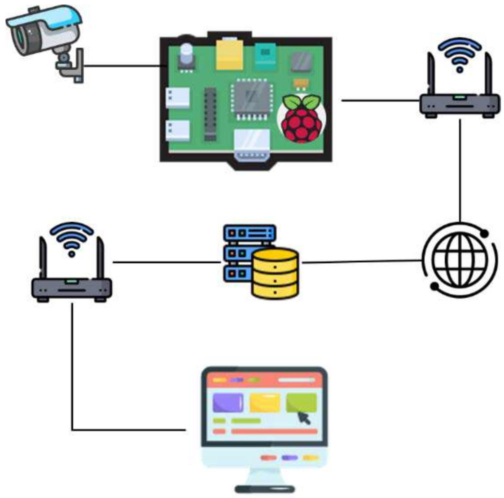

Figure 11 *Hardware implementation of the system*

The proposed methodology enables an efficient and cost-effective assessment of air pollution levels, contributing to the improvement of environmental monitoring strategies and optimization of traffic in urban areas. Additionally, within this methodology, the potential of existing cameras at intersections is utilized, eliminating the need for additional pollution measurement sensors while simultaneously maximizing the efficiency of existing resources.

4 DATA ANALYSIS AND VISUALIZATION

The collected data is stored in a database on the server and used to analyze pollution trends over different time intervals. The results are presented through a web application, shown in Figure 2, developed in Python (Flask) and JavaScript. This application allows users to interactively view pollution levels in urban areas. The interface is designed to be simple and intuitive, with a dropdown menu where users can select the station from which they want to view pollution data, along with the date and time of the measurements. As stated in the methodology, the data is displayed at two-hour intervals.

Figure 12 *Web Application: Air quality assessment at the Čačak monitoring station*

Additionally, Figure 3 presents the measurement results from another station in a different city, where the same measurement environment has also been implemented.

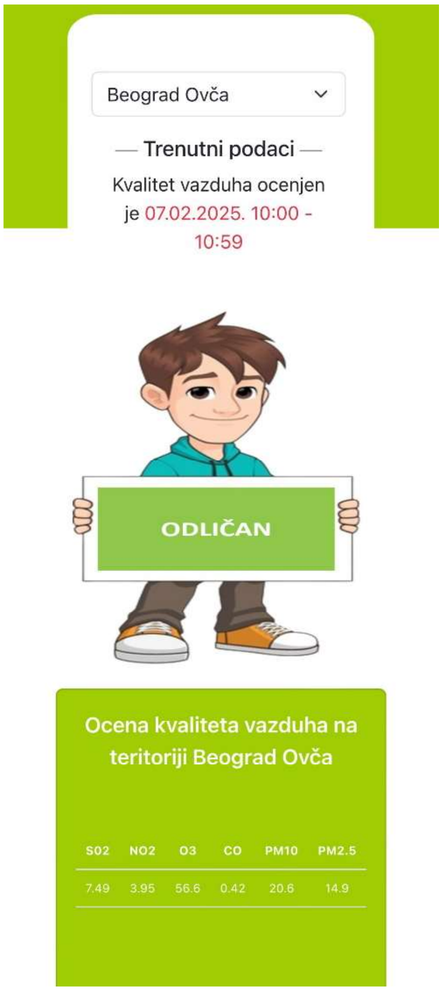

Figure 13 *Web Application: Air quality assessment at the Beograd Ovča monitoring station*

4.1 Experimental Validation and System Evaluation

The system was tested in real-world conditions in urban environments with varying levels of traffic activity. The obtained results were compared with data collected using traditional sensor-based methods for measuring air quality.

Considering the results of the experimental tests, the deviations between the pollution estimation using the mathematical model and the measurements obtained from sensor systems are negligible, especially in the case of heavy traffic. Based on the pollution calculations using the mathematical formula, the deviations range within ±7%, indicating the high precision of this model in comparison to sensor measurements. This deviation coefficient is considered realistic, given the variations that may arise due to specific traffic conditions and local factors in urban environments.

5 CONCLUSION

The objective of this paper is to present the architecture and functionality of the proposed system, analyze its reliability and efficiency through experimental results, and highlight the potential benefits of its implementation in real-world conditions. This approach can significantly contribute to improving air quality monitoring and providing city authorities and environmental organizations with valuable data for making informed decisions on environmental protection.

This study contributes to the existing body of research by introducing a method that does not require sensor deployment in public areas while simultaneously providing highly accurate air pollution assessments based on traffic parameters and computer vision. The implementation of such a system can significantly enhance environmental monitoring strategies and optimize traffic flow management in urban areas.

Future research will focus on improving the vehicle recognition model to include a broader classification of vehicles based on emissions, distinguishing between electric, hybrid, and internal combustion engine vehicles. Additionally, further enhancements may involve integrating meteorological data, such as wind speed and humidity, to achieve more precise calculations of pollutant dispersion.

Moreover, the research will expand to optimize the model for real-time processing on edge devices, such as embedded systems with low power consumption. Furthermore, the development of an adaptive model is planned, which could utilize data from drones and other sources to enable dynamic and comprehensive pollution analysis across different urban zones.

With these advancements, the proposed method could become even more relevant for practical applications in smart cities, supporting the development of sustainable strategies for reducing air pollution.

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