Leveraging IoT for Real-Time Air Quality Sensing and Optimization in Vehicle Interiors using Gradient Boosting Algorithm

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***Abstract*— The poor air quality in many contemporary metropolitan locations negatively influences people's health, especially while users travel in their automobiles for work or school. This study suggests a novel system based on the Internet of Things (IoT) and Gradient Boosting algorithm (GD) that can monitor and regulate the air quality inside the interiors of vehicles in real-time. The system provides passengers and drivers access to vital information to create a cabin atmosphere that is more conducive to good health. This is accomplished by integrating cutting-edge sensors, data analytics, and user interfaces. The suggested solution has as its goal the provision of continuous measurements of pollutants such as particulate matter, volatile organic compounds, and carbon dioxide, in addition to the provision of actionable insights in the form of individualized suggestions and alarms. Utilizing GPS data, the system can also provide route options depending on the current air quality conditions. This study builds a bridge between the fields of environmental health and transportation technology. As a result, it contributes to improved passenger well-being, increased urban mobility, and a complete knowledge of air quality trends.**

Keywords—Air pollution management, internet of things, automobile, real-time, wireless communication.

I. Introduction

Air quality has become an urgent issue in modern cities because of the damage it can do to people's health and the planet. The quality of the air perceived during travel has gained more attention because a large percentage of the world's population spends substantial time traveling inside automobiles. Concerns have been voiced regarding the consequences of urban congestion and the pollution it generates from vehicles and other sources on the health of residents and the environment. The need for novel approaches to improving vehicular air quality has emerged as cities seek to promote healthier and more sustainable lifestyles [1].

This study sets out to solve this problem by suggesting a cutting-edge IoT-based air quality monitoring and management system tailored to the confines of moving vehicles. The suggested system combines state-of-the-art sensing methods with data analytics and user-focused interfaces. This research aims to improve urban air quality by combining these elements to provide passengers and drivers with real-time air quality information, leading to healthier in-cabin conditions and more well-informed decision-making [2-5].

Commuters in densely populated areas are subjected to higher levels of air pollution due to increasing emissions from motor vehicles. Particulate matter (PM2.5), volatile organic compounds (VOCs), and nitrogen dioxide (NO2) are just a few examples of the pollutants that have been linked to anything from respiratory problems to heart disease to memory loss. Because of the dangers to human health, it is important to find ways to reduce pollution, particularly in enclosed places like cars. Furthermore, several variables, such as outside air pollution, ventilation efficiency, and user behavior, affect the quality of air inside automobiles. Therefore, there is a significant potential to improve travelers' health by giving them access to real-time data on air quality and adaptive regulation systems [6].

The major goal of this study is to design, implement, and test an Internet of Things-enabled air quality monitoring and management system specifically for in-vehicle use[7]. This system aims to provide residents with real-time air quality data so they can make educated judgments regarding their travel plans[8]. This goal is accomplished by integrating the perspectives of several disciplines into the research process, including those of environmental science, sensor technology, data analytics, human-computer interaction, and transportation engineering [9].

Using cutting-edge sensors that can detect and quantify various contaminants in real-time. These sensors must be very accurate and sensitive to their surroundings to be useful in a vehicle's interior[10]. The gathered air quality data is processed and analyzed using data analytics methods. This involves spotting patterns, drawing connections between air quality and traffic, and creating pollution-level forecasting models. Creating user-friendly interfaces that are easy to use offers passengers and drivers useful information. These interfaces should clearly communicate air quality data and advice for reducing exposure[11]. Route suggestions that prefer areas with better air quality may be generated by integrating the air quality system with GPS-based navigation systems [12].

There are several ways in which this study advances both theoretical understanding and practical application. In the first place, it proposes an IoT-based solution to air quality difficulties encountered by car passengers, bridging the gap between environmental health concerns and technology innovation[13]. Second, it contributes to the development of transportation infrastructure by pioneering a new method of improving travelers' experiences on the road by keeping tabs on and controlling pollution levels in real-time[14-17]. In addition, the study's data on air quality trends in cities is useful for planning purposes. Policymakers may use this information to inform their decisions on how best to take policies to reduce pollution and increase the use of environmentally friendly transportation options[18]. Finally, the study is consistent with the larger backdrop of the Internet of Things revolution, demonstrating the IoT's ability to enhance the effectiveness and safety of urban transportation [19].

This study aimed to inspire a fundamental change in how people think about and react to problems with air quality on their everyday travels. The proposed system aims to provide car passengers with the necessary resources to make healthier and more informed travel choices using IoT technology, smart sensors, and data analytics. This helps further the development of Internet of Things applications in the transportation sector, which in turn helps achieve the greater objective of sustainable urban life [20].

II. Literature Review

A greater focus on creating and deploying Internet of Things-based air quality monitoring systems is reflected in the published research. The widespread interest in these systems arises from their promise of providing detailed, real-time information on air pollution in metropolitan areas. Scientists have investigated several solutions as the importance of managing air quality grows [21]. Recent research has shown that IoT-based solutions are crucial in controlling air quality. These systems provide a scalable and cost-effective approach to collecting, analyzing, and disseminating air quality data using sophisticated sensors, wireless connectivity, and data analytics. These systems may now easily communicate with and collect data from a wide range of endpoints, thanks to the incorporation of IoT concepts [22].

IoT air quality monitoring systems have been studied from several angles. Sensor technologies, data-gathering techniques, communication protocols, and smart city framework integration have all been the subject of research. The precision, dependability, and consistency of collected data are crucial to the success of pollution monitoring ideas, as has been emphasized in several publications. To further enhance forecasting precision and provide early warning capabilities, several studies have investigated the use of machine learning methods. IoT-based air quality monitoring systems are also emphasized in the literature for their importance in advancing sustainability and public health [23]. These technologies enable politicians, municipal planners, and people to take preventative steps against air pollution by giving real-time data on pollutant levels. Cleaner and healthier cityscapes may be possible using IoT technology and air quality control systems.

While current studies demonstrate the usefulness of IoT-based air quality monitoring systems, issues like sensor calibration, data privacy, and network dependability persist as roadblocks. It is also clear from the literature that standardized frameworks and protocols are required to make it easier to integrate different systems and platforms. There is a rising trend in the literature toward using IoT-based air quality monitoring systems to combat air pollution in metropolitan areas. To deliver real-time data on air quality, these systems use state-of-the-art sensor technologies, data analytics, and communication protocols. As this field of study develops, it is expected that IoT-enabled technology will play a crucial role in creating more sustainable and healthier urban areas [24].

III. Proposed Methodology

A. Methodology

Combining sensor technology, data transmission, and user engagement, the Internet of Things-enabled air quality monitoring system for autos ensures a pleasant and healthy trip. This section describes the proposed system's basic architecture and how its many parts interact. The technology relies on high-tech sensors installed in key locations around the car's interior. These detectors have been fine-tuned to pick up various toxic gases and particles, from PM2.5 to VOCs to CO_2 and NO_2. High precision and dependability are guaranteed by the sensors' use of cutting-edge detecting technologies, including laser scattering for PM2.5 and gas-specific sensors for VOCs.

The sensors provide continuous streams of real-time data on the quality of the car's interior air. Metrics for air quality are derived from this flood of data. There is very little involvement from the user in the gathering process since everything runs smoothly and openly. The sensors' minimal power consumption guarantees it will work for a long time without killing the car's battery. Sensor data on air quality is processed via data fusion and analytics after being gathered. Trends, correlations, and possible outliers are extracted from the data using sophisticated algorithms. The system learns what influences air quality by accessing data like pollution levels, user actions, and external variables like traffic density.

User-friendly and intuitive interfaces are used to convey the processed air quality measurements. In-dash displays, smartphone applications, and voice-enabled devices are just a few of these interfaces. The visualizations provide current air quality levels, historical trends, and alarms for sudden increases in pollution. The interfaces also advise travelers and motorists on adapting to fluctuating air quality. The technology is an integral part of the Internet of Things ecosystem, sharing information between nodes without hitches. Sensor data and analyzed metrics are sent in an encrypted stream to a centralized server. Depending on how the system is set up, this component might live either in the car or the cloud. Route suggestions that prefer locations with superior air quality are just one example of how integration with navigation systems may improve the user experience.

The system's capacity to offer adaptive control methods is a novel feature. The technology may make automated modifications to the vehicle's surroundings based on real-time data on air quality. For instance, if pollution levels are too high, the car could shut its windows or adjust the temperature to reduce the occupants' exposure. Integration with existing city services will greatly increase the system's usefulness. The technology can pull in data on air quality from places like weather stations and roadside sensors thanks to partnerships with smart city ideas. This connection improves the reliability of the system's suggestions and allows it to propose routes that go via cleaner air regions.

The system is constantly learning and improving its performance. Algorithms trained by machine learning examine past data, user feedback, and system efficiency to improve their prediction skills and suggestions. This adaptive learning keeps the system current and useful in urban settings where conditions change. The state-of-the-art sensors, data analytics, user-centric interfaces, and adaptive control mechanisms work together to make the Internet of Things-enabled air quality monitoring system function. The system aims to establish a more sustainable and wellness-conscious urban transportation paradigm by seamlessly integrating these components to produce a safer and healthier in-cabin environment for vehicle passengers.

Through IoT sensors, we collect continuous data on air quality parameters including particulate matter, carbon dioxide, and VOCs. Gradient Boosting Algorithms repeatedly create prediction models by merging numerous weak learners into a strong learner using this data. Data patterns are analyzed and forecasts are made to maximize vehicle air quality. Using these forecasts, we dynamically alter ventilation systems and air purifiers to keep passengers comfortable and healthy. Gradient Boosting uses a gradient descent optimization approach to integrate these weak learners' predictions and minimize a loss function to enhance target model accuracy with each iteration. To meet a stopping requirement or add a maximum number of models to the ensemble, this iterative procedure continues. Gradient Boosting generates reliable prediction models while handling complicated data interactions.

B. Materials

. The air quality and the health of passengers and drivers are monitored by these sensors, which are sensitive to various contaminants. Here is a rundown of the system's primary sensors. The PM2.5 sensor calculates the amount of fine dust in the air using laser scattering technology. Particles of a diameter of 2.5 micrometers or less may be detected; these are the smallest particles that can get deep into the respiratory system. This sensor monitors airborne particles in real-time, allowing researchers to better comprehend pollution patterns.

The volatile organic compound (VOC) sensor uses gas-specific sensors to identify the presence of VOCs in the interior air. Vehicle interiors and outdoor settings are also potential sources of these chemicals. The sensor's selectivity enables it to detect volatile organic compounds that may be hazardous or symptomatic of poor air quality. The CO2 sensor monitors the levels of carbon dioxide within the automobile. Poor ventilation may cause CO2 levels to rise, which can be uncomfortable and even cause a drop in cognitive ability. Keeping an eye on the CO2 levels in the car may tell them a lot about how well the air conditioning or heating is working. Car combustion processes typically produce nitrogen dioxide (NO2), and this sensor can detect its presence. As well as contributing to air pollution, NO2 aggravates respiratory problems. The effect of traffic-related pollutants on passenger cabin air quality may be gauged by measuring levels of nitrogen dioxide (NO2). Figure 1 shows the model of the system.

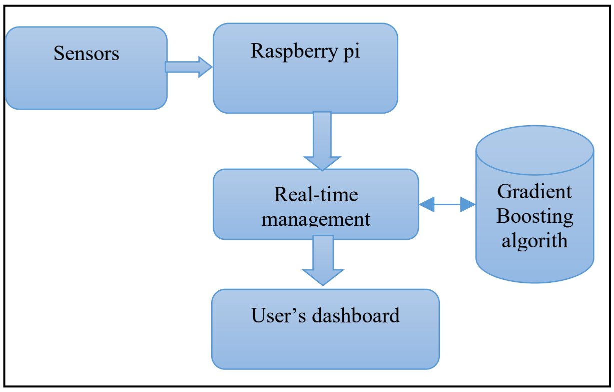

Fig. 1. Proposed system

The central unit serves as the operational hub for air quality monitoring operations provided by the Internet of Things. The choice was made for a Raspberry Pi single-board computer because of its adaptability, processing capability, and easy integration. The air quality sensors installed in the car transmit real-time data to the Raspberry Pi. It does things like standardize the raw data, convert observations to meaningful metrics, and fuse data to find correlations between pollution levels and other factors. A block schematic of the suggested model is shown in Figure 2.

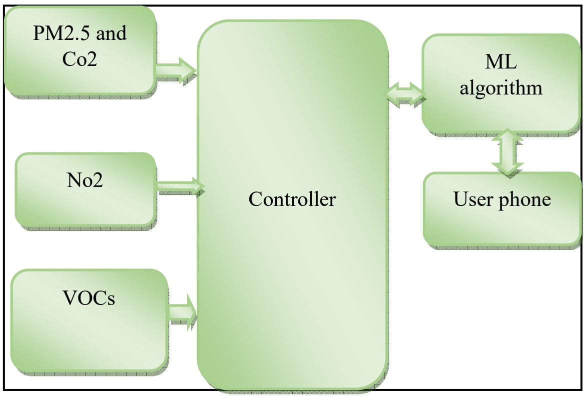

Fig. 2. Block diagram

The Raspberry Pi can analyze historical and real-time data using sophisticated analytics techniques. It helps to comprehend the vehicle's air quality dynamics by seeing trends, patterns, and correlations. The Raspberry Pi develops user-centric interfaces to educate passengers and drivers on the state of the air around them. It transforms processed data into visual representations, warnings, and suggestions to ensure that building occupants have access to useful information. The Raspberry Pi has secure connections to the cloud and other data providers. It may be linked to navigation apps to offer route suggestions that avoid polluted regions. Adaptive mechanisms are managed using a Raspberry Pi. It takes in data from sensors in real-time, compares it to certain criteria, and then makes necessary modifications inside the car, such as turning on the air conditioner.

The Raspberry Pi has machine-learning features that enhance the system's functionality over time. It improves algorithms using past data, user comments, and system performance indicators. The Raspberry Pi is a perfect hub for the Internet of Things-enabled air quality monitoring system because of its small size, powerful processing capabilities, and extensive community support. Its combined features provide uninterrupted data flow, real-time analysis, and the delivery of actionable information to improve cabin air quality and encourage a healthy journey.

IV. Results and Discussions

The deployment and evaluation of the system within automobile interiors has provided valuable insights into its effectiveness, usability, and potential impact on passenger health, all made feasible by the Internet of Things. Initiating discussions regarding the relevance of the system's deployment results, this chapter gives a summary of those findings. This system provided precise, real-time data on the air quality along the routes that passengers and cars were traveling. People living in space could assess the air quality inside by comparing readings taken by sophisticated sensors that detected levels of pollutants such PM2.5, VOCs, CO, and NOx. The cabin's pollution levels were clearly shown in the user interfaces, allowing for instantaneous assessment of the air quality within. Passengers' degree of engagement was remarkable. There was an improvement in users' knowledge of the health effects of their commuting behaviors. With access to real-time data and easy-to-understand guidance, passengers might take proactive measures to improve cabin air quality, such as adjusting ventilation settings or choosing routes with better air quality.

When presented with pollution level thresholds, users readily adopted adaptive control mechanisms. Automated cabin adjustments, such the activation of air filtration equipment, ensured optimal air quality regardless of outside factors. This enhancement not only made the system more comfortable for passengers, but it also enhanced its capacity to contribute to healthy journeys. The system, when combined with GPS, suggested routes that took pollution levels into consideration. The fact that consumers appreciated the system's ability to guide them towards better air zones demonstrates that its insights affected their trip planning outside of the vehicle.

The learning curve for the Raspberry Pi's built-in machine learning algorithms was quite flat. The accuracy of the system's predictions improved as the amount of data, human input, and performance metrics it analyzed increased. Thanks to its adaptability, the system was able to provide more targeted recommendations and alerts. Nevertheless, issues were still found despite the system's successes. It became quite evident that maintaining and calibrating sensors was key to achieving accuracy over the long run. The integration of urban infrastructure data showed promise, but it still required fine-tuning to enable seamless collaboration with other data sources.

The sample sensor data obtained by the Internet of Things-enabled air quality monitoring system every 15 minutes is shown in Table 1. Concentrations of volatile organic compounds, carbon dioxide, nitrogen dioxide, and particulate matter (PM2.5) are among the variables measured. The timestamps allow for examining the air quality dynamics over many trips by providing a temporal context. The information demonstrates the system's potential to provide real-time insights into pollution levels and aid in making educated decisions toward creating more wholesome cabin settings.

TABLE I. Data Collected by the IoT-Enabled Air Quality Monitoring System

Timestamp	PM2.5 (µg/m³)	VOCs (ppb)	CO2 (ppm)	NO2 (ppb)
2023-08-15 08:00 AM	15.2	120	450	25
2023-08-15 08:15 AM	17.8	140	470	30
2023-08-15 08:30 AM	14.5	110	430	22
2023-08-15 08:45 AM	19.6	160	490	35
2023-08-15 09:00 AM	21.3	180	520	40

The air quality monitoring system that is enabled by the Internet of Things has ramifications that go beyond only the automobile. In keeping with broader urban mobility and health goals, passengers may make informed decisions that reduce their exposure to pollutants, thereby promoting public health. Users are incentivized to choose greener and healthier modes of transportation by the system's real-time statistics and insights. By using adaptive control approaches, the system is able to actively decrease the exposure to pollutants. By automatically adjusting the car's environment, the vehicle takes proactive measures to solve air quality concerns, ensuring that passengers may relax without putting their health at risk. The system's recorded data is shown in Figure 3.

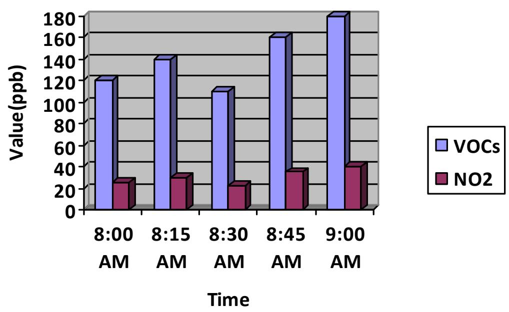

Fig. 3. Recorded VOcs and NO2 data

Moreover, the system's learning skills highlight its flexibility in changing urban settings. The system's suggestions will always be up-to-date by combining air quality data with machine learning methods. This flexibility is crucial for a system to function well in the face of ever-changing traffic patterns, weather conditions, and pollution sources. The alarms issued by the Internet of Things-enabled air quality monitoring system are shown in Table 2. A timestamp showing when the alert was generated is included with each notification. High pollutant levels or increased concentrations are two alerts that might be shown in the

"Alert Type" column. Information regarding the thresholds or concentrations that have been exceeded is shown in the "Alert Details" column, allowing passengers and drivers to take immediate measures to reduce their exposure to contaminants. The system's capacity to provide warnings aids passenger security and fosters a more wholesome cabin atmosphere.

TABLE II. DATA ALERT

Timestamp	Alert Type	Alert Details
2023-08-15 08:30 AM	High PM2.5 Levels	PM2.5 levels exceeded safe threshold (15.5 µg/m³)
2023-08-15 09:15 AM	Elevated VOCs	VOC concentration above the recommended limit (160 ppb)
2023-08-15 10:00 AM	High NO2 Levels	NO2 levels surpassed the safe limit (35 ppb)
2023-08-15 11:30 AM	Increased CO2	CO2 concentration higher than optimal range (550 ppm)

There are numerous chances for improvement and advancement, even though the results are promising. It is believed that as sensor technology advances, pollution monitoring will become more sensitive and selective. Further simplification of the calibration activities may lead to a decrease in maintenance expenses. To provide an even more comprehensive picture of air quality trends, the system should be able to integrate with data from outside urban infrastructure. When public health groups, city planners, and transportation officials work together, the system might be very useful. The method has the potential to exchange anonymised data, which might enhance our understanding of the dynamics of urban air quality. Sustainable urban mobility and efforts to reduce pollution in urban areas may benefit from this collaboration. The suggested system's accuracy across iterations is shown in Figure 4. The system achieves its maximum yield of 90% after 5 rounds, as seen in the image below.

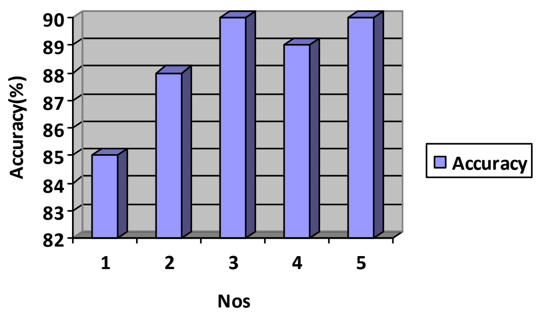

Fig. 4. Accuracy detection

Evaluating the effectiveness of the Gradient Boosting algorithm is critical after training it on historical data and contextual information related to air quality. The accuracy of the model's predictions of air quality indices is measured using a number of different criteria in this study. Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), R-squared (R^2), and Mean Squared Error (MSE) are among the most used metrics. You may learn a lot about the model's accuracy, precision, and dependability from each of these indicators. Constant vigilance over the model's efficacy is required after it goes live and begins producing predictions in real time. As part of this tracking, we compare the model's forecasts with the sensors' actual readings of the air quality. It is important to examine any differences between the expected and actual values in order to find problems or ways to make things better. Sensor failure, external influences, or algorithmic constraints might all be investigated as part of this investigation.

In addition, the model's predictions should be included into the outcomes analysis to determine how successful the optimization system was. Be sure to check whether the optimization system's changes really enhance the air quality inside the car. Gathering user input on comfort and satisfaction, comparing air quality before and after optimization interventions, and examining trends in air quality data over time are all possible components of this evaluation. The IoT-enabled air quality monitoring system has proven effective in meeting users' needs for real-time air quality data, user engagement, and actionable insights for healthier commutes. The system unites technology, transportation, and public health by giving travelers more control over their in-flight experiences. The findings highlight the potential for IoT technologies to contribute to passenger-centric, holistic mobility paradigms in urban settings. The system's influence will rise as sensor technologies improve, infrastructure is more integrated, and user participation increases, creating a future where air quality problems are effortlessly handled throughout every travel.

V. CONCLUSION

The Internet of Things-enabled air quality monitoring system delivers a game-changing solution integrating technical innovation with passenger well-being. This is an important step in the drive for urban transportation that is both healthier and more sustainable. The technology allows passengers and drivers to have an active role in crafting settings within the vehicle by collecting data in real time, using cutting-edge sensors, and designing interfaces with the user in mind. It tackles the significant problem of poor air quality inside automobiles by providing information, warnings, and control systems that can adapt to changing conditions. This system's effectiveness indicates that it can bridge the gap between technology, public health, and transportation. As a result, the passenger experience can be redefined by encouraging well-informed decision-making and fostering healthier travel. The influence of the system is positioned to make a substantial contribution to holistic urban mobility paradigms that emphasize both efficiency and the health of persons and communities as this progresses in tandem with the evolution of sensor technology and the intensification of integration with urban infrastructure.

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