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Design and construction of microcontroller-based exhaust emission measurement equipment for freight transportation

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ABSTRACT

Exhaust emissions from motor vehicles, especially freight transportation, are one of the main causes of air pollution in cities. This research aims to develop a portable and low-cost microcontroller-based vehicle emission measurement system. The system uses Arduino Uno with MQ-7 and MQ-2 sensors to detect carbon monoxide (CO) and hydrocarbons (HC) concentrations in real-time, with the measurement results displayed on the liquid crystal displays (LCD) screen. Validation is carried out by comparing the measurement results of the tool with a calibrated gas analyzer as a standard tool. The test results showed an error rate of 0.29%–1.79% for CO and 1.85%–3.84% for HC, as well as sensor stability after about 360 seconds of heating. With its compact design, easy to operate, and low cost, this system has the potential to be an alternative vehicle emission monitoring tool for field inspection and testing activities at vehicle workshops.

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1. INTRODUCTION

The growth of industrial activities and motor transportation has led to a significant increase in air pollution in urban areas. Freight vehicle emissions are known to account for the majority of urban air pollutants, particularly nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC), which directly impact air quality and public health [1]–[4]. CO and HC are harmful compounds that are toxic, disrupt the respiratory system, and contribute to the formation of troposphere ozone as well as secondary pollution. Recent studies confirm that vehicle emissions, particularly from exhaust fumes and fuel combustion, are a major factor in increasing health risks in urban areas [5].

As a mitigation measure, the Indonesian government has issued Regulation of the Minister of Environment and Forestry No. 08 of 2023 which sets the emission threshold for motor vehicles [6], [7]. However, the implementation of this policy faces the main obstacle, namely the availability of emission measurement instruments that are affordable, portable, and easy to operate in the field. Conventional emission measuring instruments are generally expensive, bulky, and impractical for use in small workshops or routine monitoring of freight vehicles. These limitations hinder the optimization of effective exhaust gas management as the key to environmental sustainability [8].

The development of semiconductor-based microcontroller and gas sensor technology has created new opportunities for developing alternative exhaust emission monitoring systems. Several studies have proposed gas sensor-based emission monitoring systems. Purwanto *et al*. [9] designed a web-based emission monitoring system, while Mena *et al*. [10], developed a distributed internet of things (IoT)-based system for real-time vehicle exhaust gas monitoring. Sai *et al*. [11] implemented an Android-based monitoring system using a Taguchi gas sensor (TGS) for exhaust gas detection. Furthermore, studies have shown that ethanol–gasoline blends can improve combustion characteristics and reduce CO and HC emissions [12], highlighting the importance of accurate and reliable exhaust gas monitoring systems.

Despite the contributions of previous research, most of the systems developed still face significant limitations: high production costs, lack of portability, and minimal field validation [13], [14]. More specifically, the integration of microcontroller-based systems for the measurement of freight vehicle emissions with operational characteristics and emission profiles that differ from passenger vehicles has not been studied in depth. Research that combines simple design, measured accuracy, and IoT integration potential for commercial vehicle-specific applications is still limited.

Based on these problems, this study designed and validated a portable exhaust emission measurement instrument based on Arduino Uno with MQ-7 (CO) and MQ-2 (HC) sensors, equipped with a 16x2 I2C liquid crystal display (LCD) module for real-time display. The novelty of the research lies in the simple yet accurate system design, which was empirically validated on five freight vehicle units and shows potential for IoT integration for continuous field monitoring [15]. The developed device offers a practical, economical, and easy-to-operate solution for monitoring emissions from freight transport vehicles in small workshops, with a margin of error below 5% and high precision, thereby supporting the implementation of Indonesia's air pollution control policy while also providing a foundation for the development of a large-scale IoT-based emission monitoring system.

2. METHOD

2.1. System architecture

The exhaust emission measurement system developed in this study is a semiconductor sensor-based design with an integrated architecture. A block diagram of the system is shown in Figure 1, which depicts the flow of signals from the gas sensor to the data display. The system consists of four main components: (1) gas sensor module (MQ-7 for CO and MQ-2 for HC), (2) Arduino Uno microcontroller-based processing unit, (3) 16×2 I2C LCD display interface, and (4) 5 volt direct current (VDC) power supply.

The MQ-7 sensor has a sensitivity to CO gas in the range of 20–2000 ppm with a working voltage of 5 VDC, while the MQ-2 sensor has a sensitivity to HC in the range of 200–10,000 ppm. Both sensors work on the principle of changing the resistance of the semiconductor material SnO_2 due to exposure to the target gas. The analog signal generated by the sensor is converted to digital via the Arduino's built-in analog-to-digital converter (ADC) (10-bit resolution), then processed using a calibration algorithm to produce gas concentrations in % (CO) and ppm (HC) [16]. The final data is displayed on the LCD in real-time. The capture scheme of the device is shown in Figure 2.

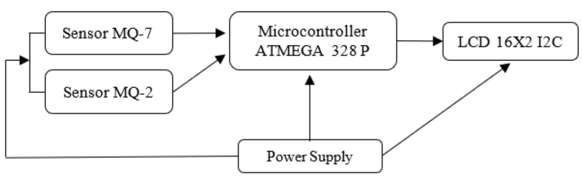

Figure 1. System block diagram

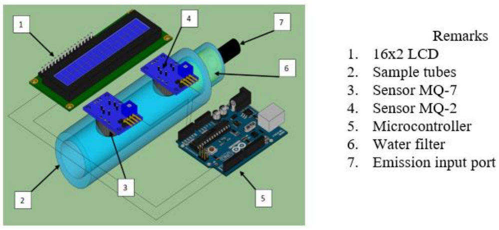

Figure 2. Device architecture

2.2. Software

The software design in implementing the CO and HC exhaust gas test equipment is based on Arduino Uno with the C programming language. The software flowchart of the tool is shown in Figure 3. The workflow of the freight vehicle exhaust emission measurement system, as depicted in the flowchart Figure 3, begins with the initialization of electronic components including the MQ-7 sensor for CO detection and the MQ-2 sensor for HC detection. The two sensors work simultaneously to capture the gas concentration level from the combustion of the engine, which is further subjected to data conversion through a series of processing: the analogue value of the ADC is converted to voltage, the resistance Rs and the Rs/Ro ratio are calculated, and then transformed to the concentration of ppm using the potential calibration equation. Specifically for CO, the ppm value is converted to percent according to emission measurement standards, while HC remains in ppm units. The final results are displayed in real-time on the 16×2 I2C LCD with CO (%) in the first row and HC (ppm) in the second row, allowing users to directly evaluate the feasibility of vehicle emissions against regulatory thresholds [17]. The system is designed on a continuous loop basis with a 2-second update interval, allowing for automatic remeasurement as per operational needs.

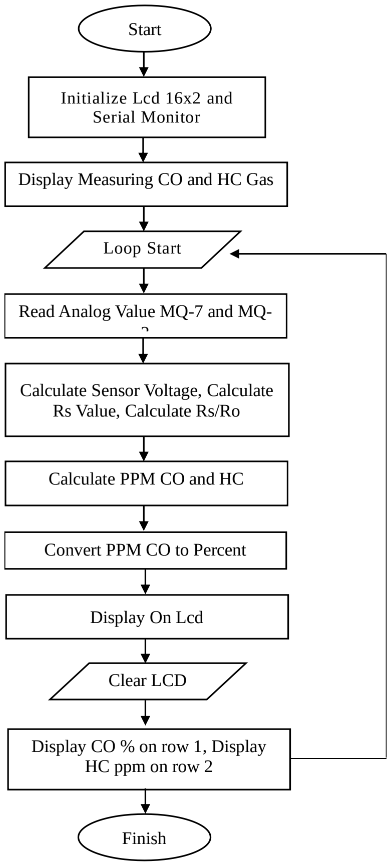

Figure 3. Software flowchart

2.3. Sensor calibration

Sensor calibration is a critical procedure to ensure the accuracy, linearity, and reproducibility of measurements. The calibration process is carried out in two main stages: sensor preparation (burn-in) and calibration with reference gas.

2.3.1. Sensor preparation (burn-in)

Tin dioxide-based (SnO_2) metal oxide (MOS) semiconductor sensors require initial thermal conditioning to achieve the electrochemical stability required in gas measurement operations [18]. The SnO_2 sensitive layer deposited on the Al_2O_3 ceramic substrate contains residual organic solvents and adsorbate water molecules that are trapped during the manufacturing process [19]. The presence of these volatile species causes sensor resistance drift under initial operating conditions, compromising measurement accuracy and reproducibility.

Process burn-in is performed by continuous heating of the sensor heating element at a nominal working voltage of 5 VDC for 24 hours in an ambient air environment with controlled temperature (25 ± 2 °C) and relative humidity (60 ± 5%) [20]. This thermal mechanism facilitates the desorption of volatile organic molecules and the reorientation of SnO_2 crystallites, leading to the stabilization of surface morphology and adsorbate oxygen concentrations. During burn-in, a redox reaction occurs at the SnO_2-air interface that forms an electron depletion layer with equilibrium thickness, determining a consistent sensor resistance (Ro) baseline. The sensor testing scheme after burn-in is shown in Figure 4.

Duration burn-in 24 hours were selected based on manufacturers' recommendations and empirical validation of previous research, which showed that this period was sufficient for short-term drift elimination and baseline stabilization of MOS sensors [21]. Inadequate conditioning has the potential to cause systematic errors in gas concentration measurements, especially in the low concentration range (<100 ppm) where the signal-to-noise ratio is critical.

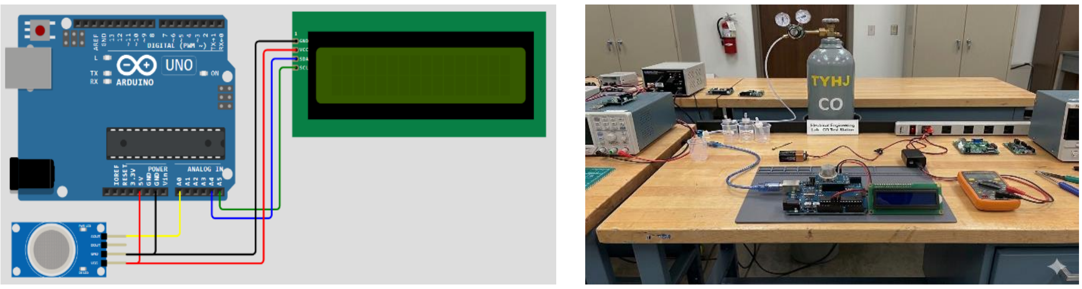

Figure 4. Testing scheme of the MQ-7 and MQ-2 sensors

2.3.2. Sponge calibration

Span calibration establishes the quantitative relationship between the sensor's electrical response and the concentration of a certified reference gas. The protocol uses standard gas CO in N_2 (50, 100, 200 ppm) and propane for HC (500, 1000, 2000 ppm) with uncertainty ±2%, delivered at 0.5 L/min to a 500 mL enclosed sample chamber [22]. 10-bit ADC readings (0–1023) converted to output voltage:

$$Vout = \frac{ADC}{1023} Vc \qquad (1)$$

The resistance of the sensor is calculated from the voltage divider with a 10 kΩ load resistor:

$$Rs = Rl.\frac{(Vc - Vout).10{,}0}{Vout} \qquad (2)$$

Ratio of resistance to baseline of clean air ($Ro = 10\ k\Omega$):

$$Ratio = \frac{Rs}{Ro} \qquad (3)$$

The concentration of gases is obtained from an empirical potential model:

$$C = a \cdot (ratio)^b \qquad (4)$$

with the constant of the MQ-7 sensor for CO: $a = 99.042$ and $b = -1.518$; the MQ-2 sensor for HC: $a = 1000.0$ and $b = -2.35$. Parameter b negative indicates a decrease in $R{\sim}s{\sim}$ as the gas concentration increases due to the redox reaction on the surface of SnO_2 [23].

2.3.3. Experimental setup

Tests were carried out on five units of gasoline-fueled goods transport vehicles with an engine capacity of 1000–2500 cc. The test site was selected in an open area with good ventilation (temperature 28–32 °C, humidity 60–75%, pressure 760 mmHg) to minimize the accumulation of exhaust gases. The testing protocol refers to the Minister of Environment and Forestry Regulation No. 8 of 2023 for category N in idle conditions [24].

Test stages: (i) the sensor is heated for 2 minutes for thermal stabilization, (ii) the vehicle is started and operated idle for 3 minutes until the engine temperature is normal, (iii) the sensor probe is inserted into the exhaust pipe at a depth of 30 cm, (iv) the measurement is taken for 7 minutes at 60 second intervals, and (v) three repetitions per vehicle. Measurable parameters: CO (%) and HC (ppm). The experimental setup is shown in Figure 5.

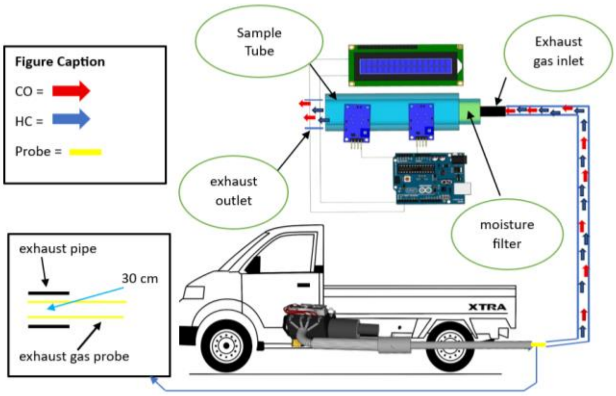

Figure 5. Experimental arrangement scheme

2.3.4. Validation and accuracy protocols

Validation of the measurement system is carried out to determine the level of accuracy of the tools developed in measuring vehicle exhaust gas concentrations. The validation process is carried out by comparing the measurement results of the developed tool with those of a certified gas analyzer commonly used in motor vehicle emission testing [25]. Figure 6 shows the standard emission test equipment and the developed measurement device employed in this comparison.

Tests are carried out on several types of vehicles with different engine capacities. Three tests were carried out on each vehicle (Test 1, Test 2, and Test 3) to obtain a more representative score [26]. The values of the three tests are then calculated on average to obtain the measurement value of the developed tool. The average value is then compared with the measurement value of the standard tool to determine the error rate of the measurement system using the mathematical (5).

Figure 6. Standard emission test equipment and design tools

$$Error = \frac{Design\ Tools - Standard\ Tools}{Standard\ Tools} x100\% \quad (5)$$

3. RESULTS

3.1. Testing of MQ-7 and MQ-2 sensors after 24 hours of burn-in

Figure 7 shows the MQ-7 sensor readings calculated by four methods based on (1)-(4). All four methods produce consistent and aligned values, thus demonstrating good suitability in representing the sensor response. Figure 7 shows that the MQ-7 sensor readings did not show stability between 60 and 300 seconds. This variability was caused by fluctuations in the output voltage, resistance ratio, and detected CO concentration, resulting in significant fluctuations in the resulting data. Stability began to be achieved between 360 and 900 seconds, with the sensor recording an output voltage of 0.557 volts, a resistance ratio of 7.497 Ω, and a CO concentration of 3.72 ppm. These results indicate that the sensor requires a warm-up period before reaching a stable operating condition and providing a more representative gas concentration reading. In this case, the sensor operates normally according to the operating principle of the MQ-7 sensor, allowing it to be installed in the overall system.

Figure 8 shows the reading of the MQ-2 sensor. The test is performed to observe the stability and consistency of the sensor's readings against the measured parameters in a given time interval. The data is recorded periodically to see changes in gas concentration values, sensor resistance ratio (Rs/Ro), and output voltage (Vout). The results of these measurements are then presented in the form of graphs to facilitate the analysis of changing patterns and evaluation of sensor performance during the testing process.

Figure 8 shows that the MQ-2 sensor readings were unstable between 60 and 360 seconds. This was due to fluctuations in the output voltage, resistance ratio, and detected HC gas concentration, resulting in significant fluctuations in the resulting data. Stability began to be achieved between 420 and 900 seconds, with the sensor recording an output voltage of 0.934 volts, a resistance ratio of 4.235 Ω, and a CO concentration of 0.41 ppm. These results indicate that the sensor requires a warm-up period before reaching stable operating conditions and providing more representative gas concentration readings. In this case, the sensor operated normally according to the operating principles of the MQ-7 sensor, allowing it to be integrated into the overall system.

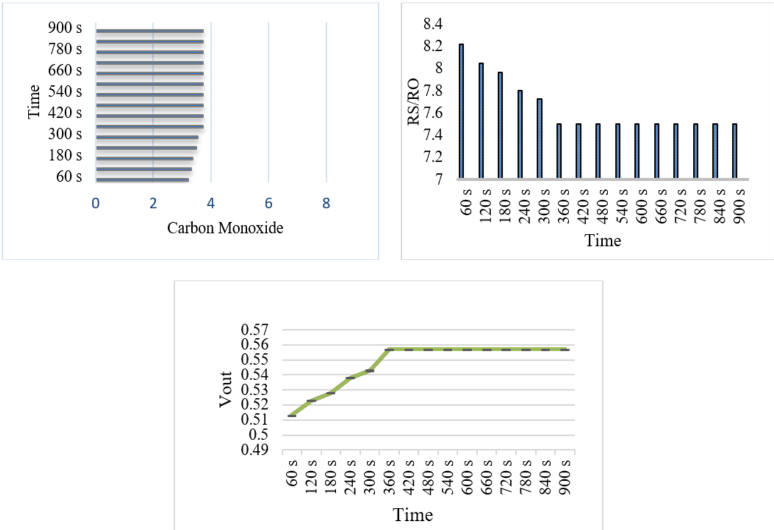

Figure 7. Curve showing CO gas reading results on MQ-7 sensor

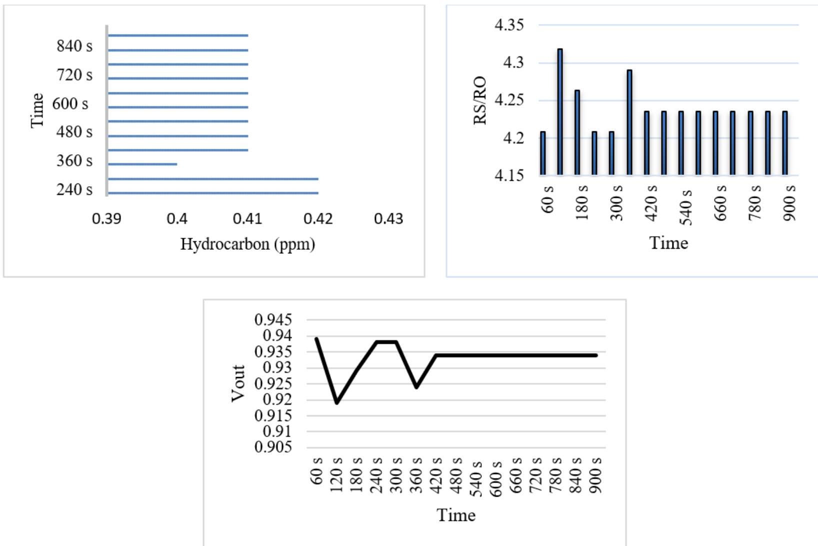

Figure 8. HC gas reading results on MQ-2 sensor

3.2. Measurement of CO gas content with standard tool comparison data

In addition to testing the consistency of readings three times on each vehicle, the measurements were also compared with standard measuring instruments (calibrated gas analyzers) used as a reference. The test was carried out under idle engine conditions with the same gas sampling procedure. Table 1 presents the comparison of CO gas concentration measurements obtained from the developed tool and the standard instrument for different vehicles. The results show error values ranging from 0.29% to 1.79%, indicating that the developed tool has a good level of accuracy and consistency in measuring vehicle exhaust gas levels. Overall, the experimental results demonstrate that the developed device is capable of producing measurements very similar to those of the KEG-200 automotive gas reference instrument, with a measurement error tolerance of less than 5%. This finding is in line with previous studies showing that modern gas emission sensor systems can provide precise and reliable measurements, especially when periodic calibration and validation are performed to maintain measurement accuracy and consistency in environmental emission monitoring [27].

Table 1. Comparison of CO gas concentration measurement results between developed tools and standard tools

Vehicles	Test 1 (%)	Test 2 (%)	Test 3 (%)	Average tool (%)	Standard tools (%)	Error (%)
Grand Max 1.5 (2023)	0.058	0.055	0.052	0.055	0.056	1.79
Grand Max 1.5 (2012)	0.220	0.219	0.219	0.219	0.218	0.46
Carry 1.6 (2009)	0.294	0.296	0.296	0.295	0.296	0.34
Carry 1.6 (2013)	0.105	0.103	0.105	0.104	0.104	0.29
Gran Max 1.5 (2020)	0.229	0.220	0.229	0.226	0.225	0.44

3.3. Measurement of HC content with standard tool comparison data

HC content testing was also compared with standard measuring instruments to determine the suitability of the design sensor readings against reference instruments. gaslain. However, the measurement results show a consistent pattern and are comparable to standard equipment, so that the tool can be declared suitable for use as a HC emission detection system for freight vehicles.

The analysis results shown in Table 2 with measurement error values from comparative testing ranged between 1.85%–3.84% in vehicle test results, a relatively small error range below 5% indicates that the design tool shows a high level of accuracy and reliability. The results of the measurement analysis show strong agreement with the results obtained from the automotive gas reference instrument KEG-200. This finding indicates that the design of the tool can function to measure HC gas concentrations accurately. This is also supported by previous research which shows that measuring HC emissions in vehicles using the emission sensing method has an error rate that can reach around 5% depending on test conditions, but is still considered reliable for vehicle emission evaluation [28].

Table 2. Comparison of HC concentration measurement results between developed tools and standard tools

Vehicles	Test 1 (ppm)	Test 2 (ppm)	Test 3 (ppm)	Average tool (ppm)	Standard tools (ppm)	Error (%)
Grand Max 1.5 (2023)	210	205	208	207.67	200	3.84
Grand Max 1.5 (2012)	315	320	318	317.67	310	2.47
Carry 1.6 (2009)	420	425	423	422.67	415	1.85
Carry 1.6 (2013)	255	248	252	251.67	245	2.72
Gran Max 1.5 (2020)	330	335	332	332.33	325	2.25

4. DISCUSSION

Test results indicate that the MQ-7 and MQ-2 sensors require a warm-up period before reaching stable operating conditions. During the initial measurement phase, there were fluctuations in the output voltage and sensor resistance ratio due to the stabilization process of the SnO_2 semiconductor material surface against oxygen molecules in the air. Reading stability began to be achieved after approximately 360 seconds, indicating that the preheating and preheating processes play a crucial role in establishing equilibrium conditions for adsorption and desorption reactions on the sensor surface [29]. This condition aligns with the characteristics of MOS semiconductor-based gas sensors, which require an activation period to achieve optimal sensitivity and response [30].

Validation of a standard gas analyzer demonstrated that the designed system has a high level of accuracy. The error value for CO measurements was in the range of 0.29%–1.79%, while the error for HC measurements was in the range of 1.85%–3.84%. This relatively small error range indicates that the sensor's analog signal conversion process via the microcontroller's ADC module and the calibration algorithm are capable of representing gas concentrations close to the KEG-200 automotive gas reference value. Thus, this microcontroller-based measurement system demonstrates good consistency in reading variations in vehicle exhaust gas concentrations.

Differences in measured emission concentrations for each vehicle also indicate that the device is capable of detecting variations in engine combustion characteristics. Vehicles with longer operational lives tend to produce higher CO and HC emission concentrations than newer vehicles [31]. The results of this study align with the study [32], which showed that increasing vehicle age contributes significantly to increased emissions due to decreased combustion efficiency and degradation of the emission control system. This is related to decreased combustion efficiency, the condition of the fuel injection system, and the quality of engine maintenance. Therefore, measured emission parameters not only describe the level of pollutants produced but can also be used as indicators of vehicle operational conditions [32]. Pollutants generated from transportation activities not only degrade air quality but also contribute to environmental disturbances that can affect public health. Exposure to pollutants and environmental stressors from transportation systems, such as traffic-related emissions and disturbances, has been reported to increase the risk of physiological and psychological health problems in communities living near transportation corridors [33].

Compared with previous studies that used microcontroller-based gas sensors for vehicle emission monitoring, the system developed in this study offers advantages in terms of simple design, low implementation costs, and high portability. The integration of the MQ sensor with a microcontroller allows for direct data processing and real-time presentation of measurement results via an LCD interface. These characteristics make the device potentially suitable for further development as a practical vehicle emission monitoring instrument for use in workshops, vehicle inspections, and IoT-based environmental monitoring systems. Overall, the results of this study indicate that the developed microcontroller-based emission measurement system is capable of providing accurate and stable results and has the potential to become an economical and portable alternative for vehicle emission monitoring.

5. CONCLUSION

This research successfully developed an Arduino Uno microcontroller-based vehicle exhaust emission measurement system with MQ-7 and MQ-2 sensors to detect CO and HC gases in real-time. The test results showed that the system had a good accuracy rate with a CO measurement error value of 0.29%–1.79% and HC of 1.85%–3.84% compared to standard tools. The sensor achieves a stable reading state after a heating process of about 360 seconds, resulting in consistent measurements. With a simple, portable, and low-cost design, the system developed has the potential to become a practical alternative vehicle emission monitoring device for field inspection activities and use in vehicle repair shops.

Further research is recommended to calibrate the system using standard gas analyzers such as non-dispersive infrared (NDIR) analyzers to improve measurement accuracy. In addition, system development can also be directed to the integration of IoT technology so that vehicle emission data can be monitored in real-time and stored in a cloud-based database. Further testing on different types of vehicles and different operational conditions is also required to improve the validity and reliability of systems developed in a variety of environmental conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

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C	:	**C**onceptualization	I	:	**I**nvestigation	Vi	:	**Vi**sualization
M	:	**M**ethodology	R	:	**R**esources	Su	:	**Su**pervision
So	:	**So**ftware	D	:	**D**ata Curation	P	:	**P**roject administration
Va	:	**Va**lidation	O	:	Writing - **O**riginal Draft	Fu	:	**Fu**nding acquisition
Fo	:	**Fo**rmal analysis	E	:	Writing - Review & **E**diting			

CONFLICT OF INTEREST STATEMENT

The authors state that there is no conflict of interest in this manuscript.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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