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The Effects of Seasonal Changes of Ambient Temperature and Humidity on Exhaust Pipe Emissions and Greenhouse Gases

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ABSTRACT

This article provides an overview of the main findings of a survey on the effects of ambient temperature and humidity on vehicular emissions of criteria pollutants and greenhouse gases. The present study is focused on the emissions of Carbon Monoxide (CO), Nitrogen Oxides (NO_X), Sulfur Oxides (SO_X), Particulate Matters (PM), Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), and Methane (CH_4) from gasoline engine passenger cars. In this analytical research, the International Vehicle Emissions (IVE) model was operated, using long-term meteorological data to determine the effects of various ambient temperature and humidity levels on exhaust pipe pollutants and greenhouse gas emissions. The results of present study indicated that as the ambient temperature increases from -7.5 °C to 20 °C, CO, NO_X, and CH_4 emissions decrease by 35.8%, 6.46%, and 21.44%, respectively, while SO_X, PM, CO_2, and N_2O emissions remain constant. In contrast, increasing the ambient temperature from 20 °C to 37.5 °C increases the emissions of all the investigated pollutants and greenhouse gases. On the other hand, the findings showed that as the ambient humidity increases from 8% to 98% CO and CH_4 emissions increase by 7.3% and 2.13%, respectively; while NO_X emissions decrease by 16.84%. However, humidity changes did not have noticeable impact on the emissions of SO_X, PM, CO_2, and N_2O. This study concluded that changes in meteorological parameters over a certain period of time, not only affect global warming, but also the emissions of criteria pollutants.

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INTRODUCTION

The relationship between vehicular emissions and meteorological parameters has attracted considerable attention. The effects of global average surface temperature increase on climate change-related concerns, including decreasing snow cover, increasing precipitation, and habitat loss and alteration for different plants and animals are evident (Masson-Delmotte et al., 2021; Hartfield et al., 2018). However, the effects of changes in temperature and humidity level could not be confined to mentioned consequences, and it can have a noticeable impact on the emissions of pollutants and greenhouse gases from the exhaust pipe of gasoline engine passenger cars (Luján et al., 2018; Luján et al., 2019).

Over the past decades, the rapid rise of urbanization and industrialization led to significant rising in number of passenger cars in Tehran province. The majority of these vehicles are light gasoline engine passenger cars, including many very polluting and obsolete cars. Therefore,

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passenger cars are one of the primary sources of criteria pollutants, hazardous pollutants, and greenhouse gas emissions (Hassani & Hosseini, 2016; Shahbazi et al., 2016; Arhami et al., 2017; Hoseinifar et al., 2023).

Aside from ambient temperature and humidity, various factors including accumulated mileage, vehicle fleet, vehicle speed, and fuel specifications affect on-road vehicle emissions. A significant correlation has been found between emissions and the factors mentioned above in many studies. (Zhang et al., 2018) analyzed the effects of cumulative mileage (deterioration) and technology change (emission standards) on the Emission Factors (EF) of exhaust pipe pollutants (CO, HC, NOx) in spark-ignited passenger cars based on Inspection and Maintenance (I/M) data by the roller test bench method. They concluded that the average EFs of CO, HC, and NOx were remarkably linearly correlated with cumulative mileage in most cases. Another study by (Shrestha et al., 2013), used the International Vehicle Emissions (IVE) model to explore the impact of technology and activity of on-road transport fleet on the emissions. As a result, buses account for the absolute majority of PM (93%), Black Carbon (BC) (99%), and NOx (91%) emissions, while motorcycles account for the majority of CO, VOCs, and hazardous air pollutants (50-79%). In another study in Seoul, South Korea, a team of scientists examined the effects of vehicle speed on the emissions of criteria air pollutants from passenger vehicles and found that the average vehicle speed in central Seoul was only 18.2 km/h, while CO, HC, NO_X, and CO_2 emissions can be reduced by improving traffic flow and rising the average vehicle speed close to 24.6 km/h (Jung et al., 2011). Also in another study, researchers reached in conclusion that limiting vehicle entrance to the Sadr overpass caused the increase in average vehicle speed by 48.6%, and consequently reduced CO emissions by 22.17% (Alisoltani et al., 2020). In another study in Mexico, (Koupal & Palacios, 2019) analyzed the effects of new fuel specifications on vehicle emissions in different areas of Mexico City, and the results of this study indicated that the evaporative VOC emissions are influenced by gasoline Reid Vapor Pressure and ethanol content, therefore fuel characteristics modification will noticeably affect the amount of evaporative VOC emissions.

As shown in the previous paragraph, factors related to the vehicles can have an evident effect on emissions in many aspects. Apart from these factors, environmental parameters including ambient temperature and humidity are the other noteworthy factors that can affect the primary and secondary air pollutants emission from vehicles (Ghaffarpasand et al., 2021). Since 1880, combined land and sea temperatures have increased on average rate of 0.08 degrees Celsius per decade; however, the average temperature rise (0.18 °C) since 1981 has more than doubled (Lindsey & Dahlman, 2020). In addition to increasing global average surface temperature, climate change may affect exhaust pollutants and greenhouse gas emissions (Ng et al., 2021). This analytical research study is focused on identifying the effects of changes in ambient temperature and humidity on vehicular emissions. Specifically, the effects of annual temperature rise on exhaust pipe pollutants and greenhouse gas emissions.

The aim of this study is to determine the impacts of ambient air temperature and humidity on the exhaust pipe emissions of local pollutants, namely, CO, NO_X, SO_X, and PM, as well as the emissions of greenhouse gases including CO_2, N_2O, and CH_4 from gasoline engine passenger vehicles.

MATERIALS AND METHODS

In this analytical research study, daily temperature and relative humidity data for an extended period of thirty years from 1990 to 2020 were used to ensure the reliability of meteorological data (Iran Meteorological Organization, 2020). In addition, this research has adopted New European Driving Cycle (NEDC) as the driving cycle. The amount of lead, sulfur, and benzene in gasoline was recorded in 2020 by using the Tehran Air Quality Control Company's fuel analysis (Tehran Air Quality Control Company, 2020). Moreover, all driving characteristics data such as daily mileage, daily start-ups, and average speed in 2020 were provided by the Tehran Traffic Model (Transport and Traffic Deputy of Tehran Municipality, 2020). Also, to calculate the average road gradient, we used the Google Earth software's path tool to draw two east-west and north-south paths in the coordinates of Tehran, and as a result, we assume that the average slope of the road is 3%.

Other than driving style, meteorological conditions, and fuel characteristics, it is also essential to correctly determine the technology distribution of the passenger vehicle fleet operating in our study area. In the current work, all investigated vehicles were passenger cars, which according to the IVE model classification, belong to the Auto/Small Truck group. Gasoline was designated as the fuel of choice for vehicles. According to the IVE model, spark-ignited engine cars were classified into two various categories based on engine size, i.e., 28% of passenger cars in Tehran have a displacement of less than 1.5 liters, and the rest are cars with a displacement of 1.5 liters or more and less than 3 liters. It should be mentioned that all vehicles in this analytical study were equipped with Multi-Point Fuel Injection (MPFI), 3-Way Catalyst (3WY), and Positive Crankcase Ventilation (PCV) system. Items mentioned previously, and travel fraction for each technology type are summarized in Table 1.

As previously mentioned, in this study the impact of ambient temperature and humidity on the emissions is determined by the IVE model. The IVE model is a computer software developed for estimating emissions from different kinds of motor vehicles. This model predicts the emissions of regional criteria air pollutants, greenhouse gases, and hazardous air pollutants (ISSRC, 2008). This model is particularly developed for developing countries to predict vehicular emissions. One of the advantages of this model is its high sensitivity to present driving style and vehicle technologies in the study region (Ghadiri et al., 2017; Zhang et al., 2018). The IVE model is able to predict how different scenarios will affect vehicular emissions based on a thorough understanding of traffic volume, vehicle composition, road length, speed record, and specific parameters of the study area (Shafie-Pour & Tavakoli, 2013; Pinto et al., 2020).

The impacts of changes in meteorological parameters on criteria pollutants and greenhouse gas emissions were calculated based on daily values of weather data in three decades (1990 to 2020) (as shown in Table 2).

Datasets generated by creating an arithmetic sequence between the extreme values. All other inputs to the IVE model were maintained constant, except the meteorological datasets that were entered separately into the model. The emissions of criteria pollutants and greenhouse gases related to each input data were determined. Finally, the scatterplots were drawn to illustrate the sensitivity of vehicular emissions to fluctuations in ambient air temperature and relative humidity.

Sensitivity analysis examines how variations in the output of a mathematical model are attributed to variations in its input elements. In this comprehensive description, the nature of

Table 1. Defined technologies for passenger vehicles in Tehran

Vehicle type	Fuel	Technology	Accumulated mileage (×103 km)	Travel fraction (%)	AC equipped fraction (%)
Light	Gasoline	MPFI: 3WY: PCV	<79	15.63	100
Light	Gasoline	MPFI: 3WY: PCV	80–161	9.38	100
Light	Gasoline	MPFI: 3WY: PCV	>161	3.13	100
Medium	Gasoline	MPFI: 3WY: PCV	<79	43.75	100
Medium	Gasoline	MPFI: 3WY: PCV	80–161	21.88	100
Medium	Gasoline	MPFI: 3WY: PCV	>161	6.25	50

Table 2. Minimum and maximum daily meteorological parameters

Meteorological parameter	Parameter value	Date
Minimum temperature (°C)	-7.7	01/08/2012
Maximum temperature (°C)	37.6	07/17/2003
Minimum humidity (%)	8	08/09/2014
Maximum humidity (%)	97.125	01/04/1991

the approach, the level of complexity, and the objective of the sensitivity analysis will vary considerably depending on the modeling domain and main application goals (Pianosi et al., 2016). Following (Saltelli et al., 2008; Pianosi et al., 2016), this analysis method is considered to be useful to serve a variety of purposes, including:

· Ranking (or Input Prioritization) aims to rank the input parameters X_1, X_2, …, X_M according to their corresponding contribution to the variability of the result.

· Screening (or Input Fixing) aims to identify input parameters that have an insignificant effect on the variability of the result.

· Mapping aims to specify the regions of the input variation space that makes meaningful extremum results.

Therefore, in this study, input factors that had a negligible impact on the exhaust pipe emissions of local pollutants or greenhouse gases and the regions of the ambient air temperature and humidity variability space that generate extreme amounts of emissions have been determined.

RESULTS AND DISCUSSIONS

Ambient temperature is one of the key factors affecting vehicular emissions. Figure 1 is extracted from the average daily temperature data received from Iran Meteorological Organization. To determine the annual temperature, monthly average temperature and average temperature of each year between 1990 and 2020 were calculated based on the aforementioned daily temperature data. The data presented in Figure 1 indicate that 1992 and 2010 were the coldest and warmest years of this period with temperatures of 16 °C and 19.5 °C, respectively. Based on the trendline equation of this chart and general pattern of the data, Tehran's average annual temperature has increased by 1.25 °C over the past thirty years (Iran Meteorological Organization, 2020).

Ambient temperature can have a noticeable impact on criteria pollutants and greenhouse gas emissions, which are the main goal of this research study. Figures 2 and 3 represent a significantly strong correlation between ambient air temperature and various pollutants and greenhouse gas emissions. The results indicated that while the ambient air temperature increases from -7.5 °C (minimum daily temperature recorded in the last thirty years) to 20 °C, the exhaust pipe emissions of CO, NO_X, and CH_4 decrease by 35.8%, 6.46%, and 21.44%, respectively, and the emissions of SO_X, PM, CO_2, and N_2O remain constant. However, as the ambient temperature increases from 20 °C to 37.5 °C (maximum daily temperature recorded in the last thirty years), CO, NO_X, SO_X, PM, CO_2, N_2O, and CH_4 emissions increase by 81.09%, 74.48%, 28.89%, 28.24%, 29.07%, 26.91%, and 32.8%, respectively. It should be pointed out that according to Figure 1, the lowest and highest annual average temperatures measured over the last thirty years are 16 °C and 19.5 °C. Assuming average annual temperatures continue to rise and exceed the tipping point of 20 °C, annual emissions of exhaust pipe pollutants and greenhouse gases will increase significantly.

In a study conducted in Spain total hydrocarbon emissions at -7 °C are 2.5 times higher than emissions at 20 °C. CO emissions are highly dependent on the air-fuel ratio, so CO is less dependent on ambient temperature, and its emission is higher at 20 °C compared to -7 °C as

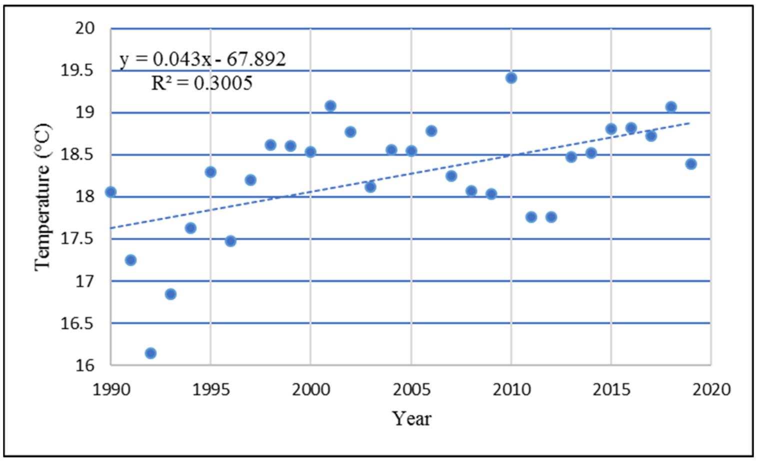

Fig. 1. Average annual temperature in Tehran

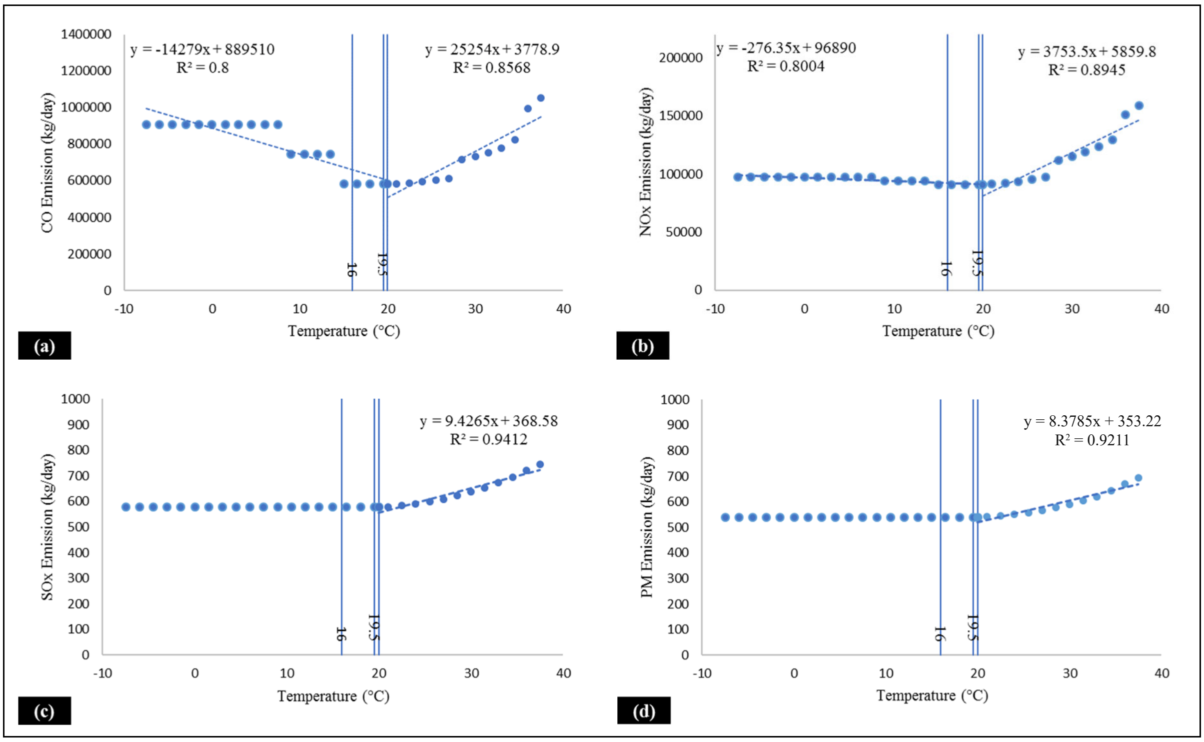

Fig. 2. Effects of ambient temperature on the emissions of pollutants, (a) CO, (b) NO_X, (c) SO_X, and (d) PM

the air-fuel ratio is higher at lower ambient temperatures (Luján et al., 2018). In current study, however, all vehicles were equipped with MPFI, and this system ensures an appropriate air-fuel ratio to the engine by electrically injecting fuel under different driving conditions (Gupta et al., 2013); thus, the results of this study are independent of the air-fuel ratio. This study's findings are also consistent with another recent study on the negative effects of low ambient air temperatures on vehicular emissions. This survey explains the effects of ambient temperature by measuring the emissions of criteria pollutants at -7 °C and 20 °C. They reached in conclusion that in NEDC, reducing the ambient temperature to -7 °C increases the emissions of HC, CO, and NO_X by 270%, 125%, and 250%, respectively (Luján et al., 2019).

Humidity is another parameter that can affect the emissions of pollutants and greenhouse

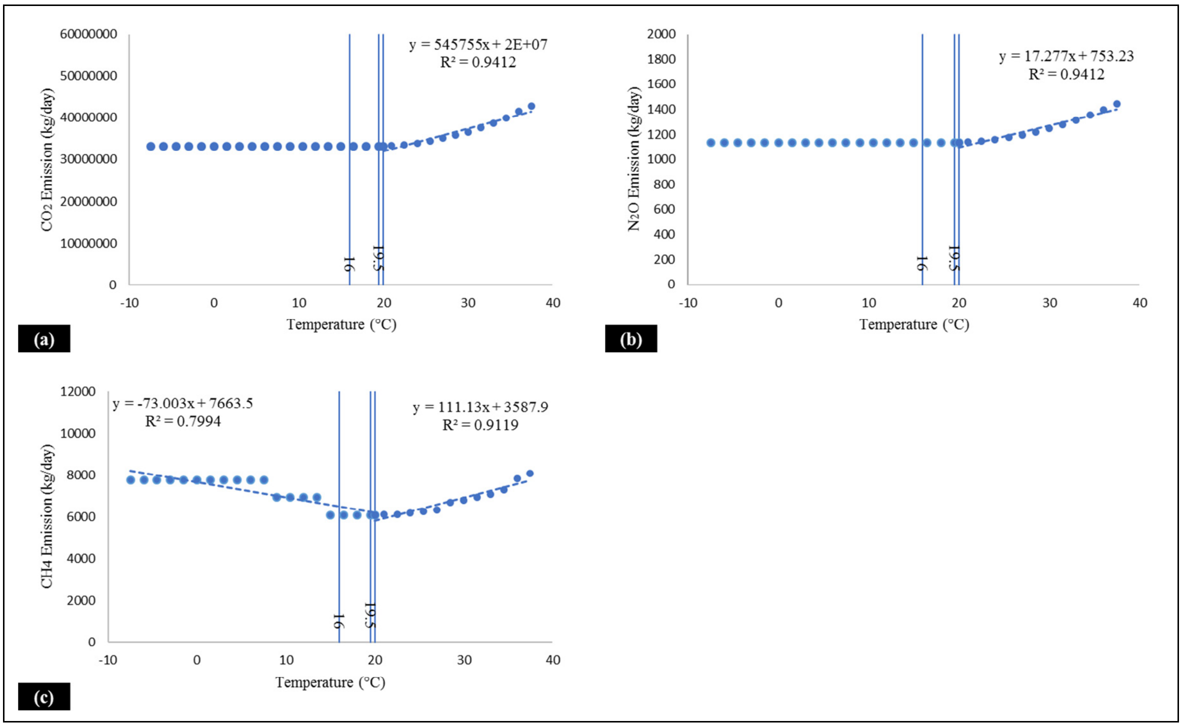

Fig. 3. Effects of ambient temperature on the emissions of greenhouse gases, (a) CO_2, (b) N_2O, and (c) CH_4

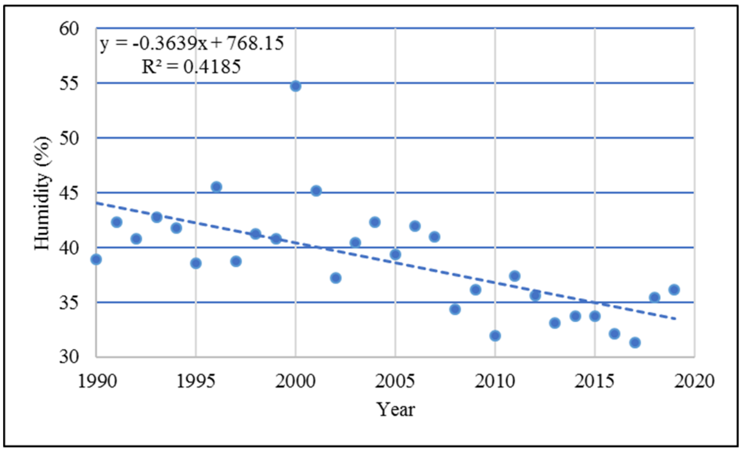

Fig. 4. Average annual humidity in Tehran

gases from vehicle exhausts. As Figure 4 shows, Tehran's average annual humidity has decreased over the past thirty years. This parameter varies throughout the day due to temperature and cloud formation (Zalakeviciute et al., 2018). The results of our study demonstrated a direct correlation between humidity and emissions of CO and CH_4 and an indirect correlation between humidity and emissions of NO_X (see Figure 5). Increasing humidity from 8% to 98% (the lowest and highest daily humidity levels recorded in the last thirty years) increased daily CO and CH_4 emissions by 7.3% and 2.13%, respectively; however, NO_X emissions decreased by 16.84%. Changes in relative humidity did not significantly affect the emissions of SO_X, PM, CO_2, and N_2O. From the findings of this study, it can be inferred that CO and CH_4 emissions increase during the wet seasons, and NO_X emissions increase during the dry seasons. These results are congruent with other studies dealing with relationships between humidity and emissions. Some

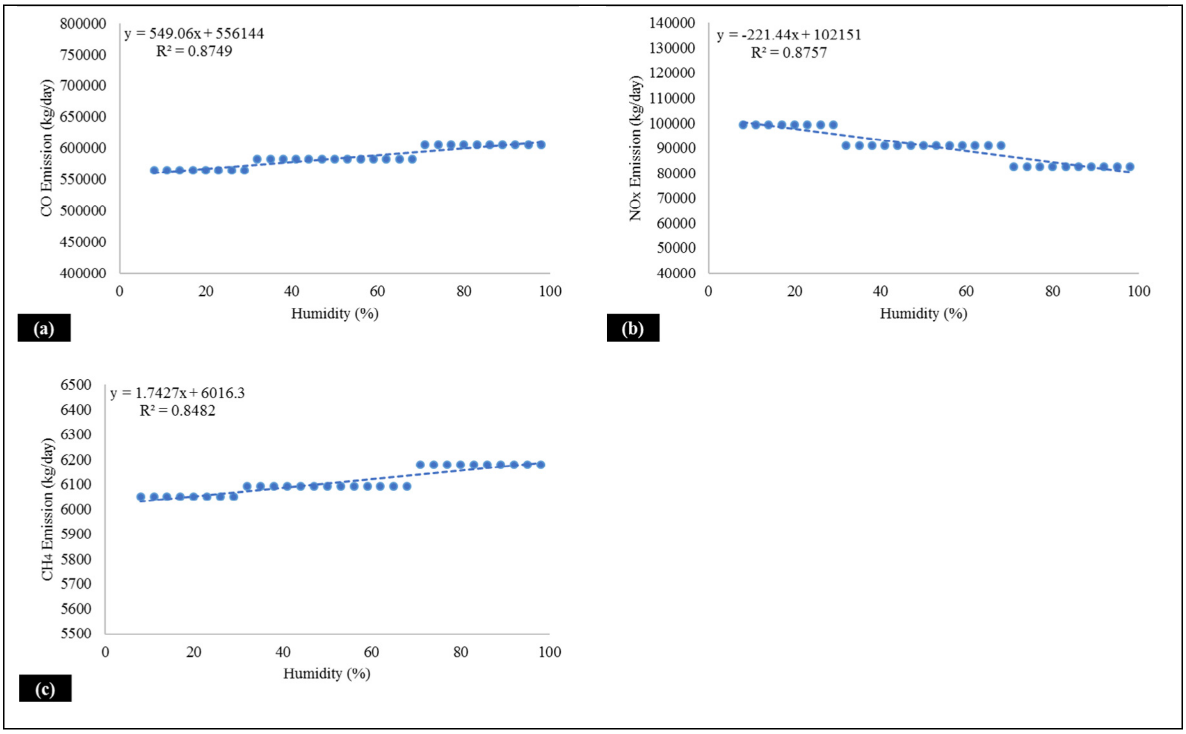

Fig. 5. Effects of ambient humidity on the emissions, (a) CO, (b) NO_X, and (c) CH_4

of these studies are briefly referenced below.

Environmental Protection Agency (EPA) has supported and financed a study on sensitivity analysis of the MOtor Vehicle Emission Simulator (MOVES) model. (Choi et al., 2010) analyzed the sensitivity of the model to ambient humidity and temperature. They inferred that NO_X emissions are influenced by both the direct effects of humidity regulation and the indirect effects of air conditioning regulation. They also reported that HC and CO emissions from both gasoline and diesel vehicles are affected by relative humidity only indirectly through air conditioning adjustments applied at temperatures above 24 °C.

Another study conducted in 2020 regarding the effects of ambient temperature and specific humidity on vehicular emissions. They found that the sensitivity of the emission ratio to humidity is less than temperature. The results of this study showed that both $\Delta CO/\Delta NO_X$ and $\Delta CO_2/\Delta NO_X$ increase slightly with increasing specific humidity during a day (Hall et al., 2020).

In 2003, (Pekula et al., 2003) published an article on analyzing the effects of relative humidity on the idling emissions of diesel engine heavy trucks. In this study, in an environmental chamber, they used a 1998 Freightliner vehicle idling at 1200 RPM to examine the effect of relative humidity on the emissions. They performed two experiments at 18 °C and 32 °C, with the relative humidity increased at a rate of 0.89% RH/min and 0.63% RH/min, respectively. Findings showed that the NO_X values decrease with increasing supply air humidity.

CONCLUSIONS

The effects of ambient temperature and humidity on tailpipe emissions of pollutants and greenhouse gases have been analyzed in this paper. This process is made possible by evaluating IVE model outputs concerning different temperatures and humidities. The results indicated that the estimated model emissions vary significantly with ambient temperature and humidity. As the ambient temperature increases from -7 °C to 20 °C, the emissions of SO_X, PM, CO_2, and N_2O remain constant, while the emissions of CO, NO_X, and CH_4 decrease. In this study, all pollutants and greenhouse gas emissions examined exhibit an increase as the ambient temperature rises from 20 °C to 37.5 °C. Notably, the critical ambient temperature for CO, NO_X, and CH_4 emissions is 20 °C. It has been observed that below this threshold, an increase in temperature results in a reduction of emissions, while above this level, rising temperature leads to an increase in emissions. Furthermore, it is expected that the rise in the average annual temperature beyond the critical threshold of 20 °C will result in an increase in the levels of pollutants and greenhouse gas emissions from passenger cars. This phenomenon, in conjunction with the broader impacts of global warming, is a matter of great concern. The escalation of greenhouse gas emissions results in higher global surface temperatures, which in turn leads to a surge in the emissions of greenhouse gases including CO_2, N_2O, and CH_4 from vehicle exhausts. This process creates a climate feedback loop that amplifies both global warming and the emissions of pollutants and greenhouse gases. It should be noted that the emissions of SO_X, PM, CO_2, and N_2O exhibit no discernible sensitivity to fluctuations in ambient relative humidity. However, as ambient relative humidity levels rise, CO and CH_4 emissions increase, while NO_X emissions experience a decrease. Consequently, CO and CH_4 emissions tend to increase during wet seasons, whereas NO_X emissions increase during dry seasons. In conclusion, it is recommended to impose traffic restriction policies during periods in which meteorological parameters cause the escalation of pollutants and greenhouse gas emissions to mitigate the detrimental impacts of vehicular emissions on global warming.

RECOMMENDATIONS FOR FURTHER RESEARCH

The present study can be interpreted as an initial step in the survey on the effects of ambient temperature and humidity on vehicular emissions. The findings of this study showed that increasing the ambient temperature from 20 °C to 37.5 °C increases the emissions of all the investigated pollutants and greenhouse gases. Furthermore, increasing humidity from 8% to 98% increases CO and CH_4 emissions; however, the emissions of NO_X decrease in lower humidities.

Therefore, future research should examine the probable effects of different ambient temperatures and humidities on the other indirect factors influencing vehicular emissions, namely, engine ignition timing, engine load, engine thermal management system, and air conditioning system. Future research could also contribute to a deeper understanding of the effects of ambient temperature on catalyst performance.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

ABBREVIATIONS

3WY= 3-Way Catalyst
BC= Black Carbon
CH_4= Methane
CO= Carbon Monoxide
CO_2= Carbon Dioxide
EF= Emission Factors
EPA= Environmental Protection Agency
HC= Hydrocarbons
IVE= International Vehicle Emissions
MOVES= MOtor Vehicle Emission Simulator
MPFI= Multi-Point Fuel Injection
N_2O= Nitrous Oxide
NEDC= New European Driving Cycle
NO_X= Nitrogen Oxides
PCV= Positive Crankcase Ventilation
PM= Particulate Matters
SO_X= Sulfur Oxides

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