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Research Paper

Assessment on the Impacts of Vehicle Speed and Slope on Tailpipe Emissions Using Desirability Function Analysis

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Abstract

Pollutant emissions from vehicles can significantly increase when driving on a road with a positive slope, according to previous studies. In internal combustion engines, minimizing tailpipe emissions like carbon monoxide (CO) and hydrocarbon (HC) by using different strategies increases carbon dioxide (CO_2). This likely contributes to global warming through the greenhouse effect. This study aimed at determining the effect of road slope and vehicle speeds on tailpipe emissions, such as CO, HC, and CO_2. Full factorial analysis was employed for the design of the experiment. An experiment was conducted in Addis Ababa, Ethiopia, using a portable emissions analyser and Global Positioning System (GPS) to collect emissions data from passenger vehicles at a speed of 10, 20, 30, 40, and 50 km/h and road slopes of -2, 0, 2, 4, and 6 degrees. The regression models developed for CO_2, CO, and HC were acceptable, with R-squares of 98.0, 92.9, and 84.9 %, respectively. Finally, desirability function analysis was employed to simultaneously optimize the responses to identify optimum points that minimize CO, HC, and CO_2 formation. The most preferable speed to simultaneously reduce CO, HC, and CO_2 emissions was found to be 40 km/h on a level road and 30 km/hr on a 2-degree road slope with composite desirability of 0.83 and 0.72, respectively. As a conclusion, it is shown that the use of desirability function analysis can effectively be used to identify the optimum driving speed at which CO, HC, and CO_2 emissions are minimized simultaneously for the given road slope.

1. Introduction

Fuel combustion in vehicle engines results in exhaust emissions, which contribute greatly to air pollution in urban areas due to the usage of gasoline and diesel fuels (Sati & Dare, 2022). Earth's atmosphere is being degraded by exhaust products such as carbon monoxide (CO), hydrocarbons (HC), and carbon dioxide (CO_2) (Ziolkowski et al., 2023). Air quality deteriorates every day as more and more vehicles are added to the road (Sarkan et al., 2022). Increased vehicle and population densities in urban areas exacerbate traffic congestion, which has detrimental effects on social, economic, and environmental aspects of life (Shepelev et al., 2023). Numerous factors, such as vehicle's design, engine performance, the surrounding environment, road slope, and operating conditions, have an impact on emissions from vehicles (Liu et al., 2019). Average emission rates

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as a result of the road's slope increases the vehicle's power at a given speed (Meng et al., 2023). Most researchers are currently concentrating on road vehicular emissions measurement (Bante et al., 2021). Vehicles are a major factor in the transport sector's overall contribution to greenhouse gas emissions (GHG). This in turn has a negative effect on global warming (Gopal et al., 2023). Europe, USA, China and Japan have implemented fuel economy standards to reduce CO_2 emissions and fuel consumption (Zhou et al., 2023).

Therefore, it is essential to do on-road testing, measure the amounts of pollution the vehicles emit, and make informed decisions about reducing its carbon footprint by looking at CO_2 emissions. There has been an in-depth investigation of the previous studies on vehicle emissions. Only a few research that are pertinent to this study's focus on the impact of road slope on tailpipe emissions are considered here. According to the investigation by Meng et al. (2023), the average emissions rates were sensitive to road slope and vehicle-specific power (VSP) variation; an increase in gradient and VSP resulted in an increase in average emissions. Cvitanic et al. (2023) recently investigated how road alignment affects a vehicle's fuel consumption and emissions and Posada-Henao et al. (2023) investigated the impact of vehicle weight and road gradient on truck fuel consumption.

Meng et al. (2023) investigation result showed that three to six times more emissions are generated by roads with grades of greater than 3% than those with grades of less than -3%. A study by Liu et al. (2019) found that disregarding grade at +2% grade level underestimates fuel consumption rate and particulate matter (PM) 2.5 emissions by 12%. It has been found by Costagliola et al. (2018) that a road slope of 5% results in almost a 100% increase in CO_2 compared with a flat road. However, a road grade of -4% results in a nearly 70% reduction in CO_2, and 4-5% grades result in 2 to 5 times more NO_X emissions when compared with level roads. Therefore, when designing roads, it is important to consider the road grade and its effect on emissions. It is also important to consider the environmental impact of different road grades when selecting the most efficient route for travel. A road grade of 0-5 % results in 65-81 % increase in CO_2 and 85-115 % increase in NO_X (Gallus et al., 2017). Triantafyllopoulos et al. (2019) found a three-times increase in CO_2 emissions and eight times increase in NO_X emissions when dynamic driving is combined with driving uphill.

According to Pavlovic et al. (2020), the fuel consumption deviation increases with increasing road grade compared to laboratory results. In addition, Salihu et al. (2023) found that CO, HC, and NO_X emissions are more sensitive to increases at uphill than at downhill slopes. In an internal combustion engine, minimizing pollutant gas emissions like CO and HC by using different strategies causes CO_2 to be increased. Researchers have studied the impact of the road slope on vehicle emissions, but the best driving speed at which CO, HC, and CO_2 emissions are simultaneously minimized has not been studied for different slopes of the roads. To reduce CO, HC, and CO_2 emissions simultaneously, and to better understand the effects of the vehicle speed and road slope on emissions, in this study a full factorial analysis and desirability function analysis were applied to the chosen urban road. Based on the findings, CO, HC, and CO_2 emissions on urban roads could be reduced simultaneously. An effective strategy for lowering emissions from internal combustion engines is offered by this method. Using this approach, plans for reducing emissions from various vehicle types can be developed.

2. Materials and Methods

To collect data for this study, gasoline and diesel fuelled vehicles, portable emissions tester, Global Positioning System (GPS), and laptop were used. The research method was experimental involving vehicle selection, route selection, emissions measurement, and results analysis using full factorial and desirability analysis. The measurement of the tailpipe emissions was performed using a portable emissions tester from two passenger vehicles and flow chart for the study is presented in Figure 1. For the location identification, On-Board Diagnostic (OBD)-II-based GPS was used to measure road slope. The experiment data was analysed and interpreted using MINITAB 21 software and graphs were plotted using OriginPro 2022.

2.1. Study area

Experimental data collection was conducted in Addis Ababa, Ethiopia, using the range of road slope considered in design of the experiment. Figure 2 (a-d) shows, four routes selected as the case study sites. The OBD-II-based GPS was installed in the experimental vehicles for detecting road slopes and recording location information.

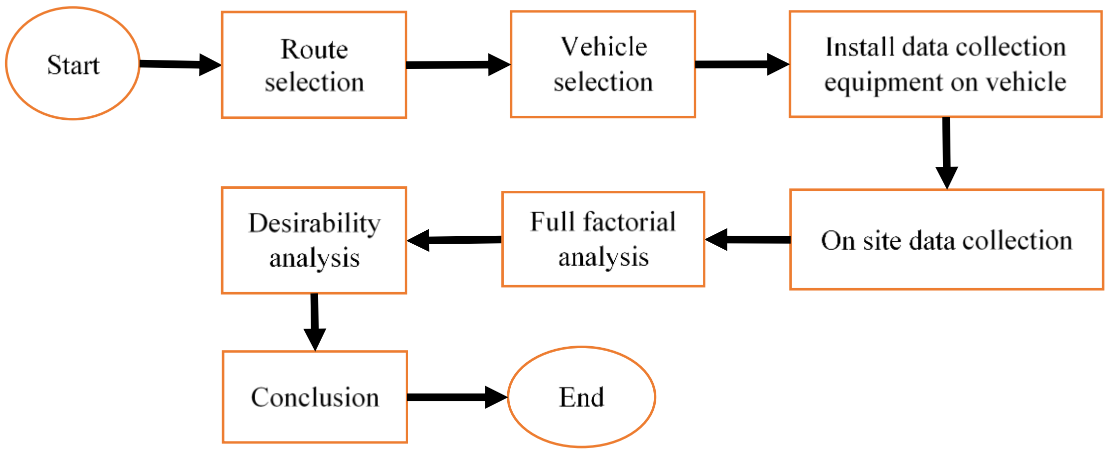


Figure 1: Flow chart for the study

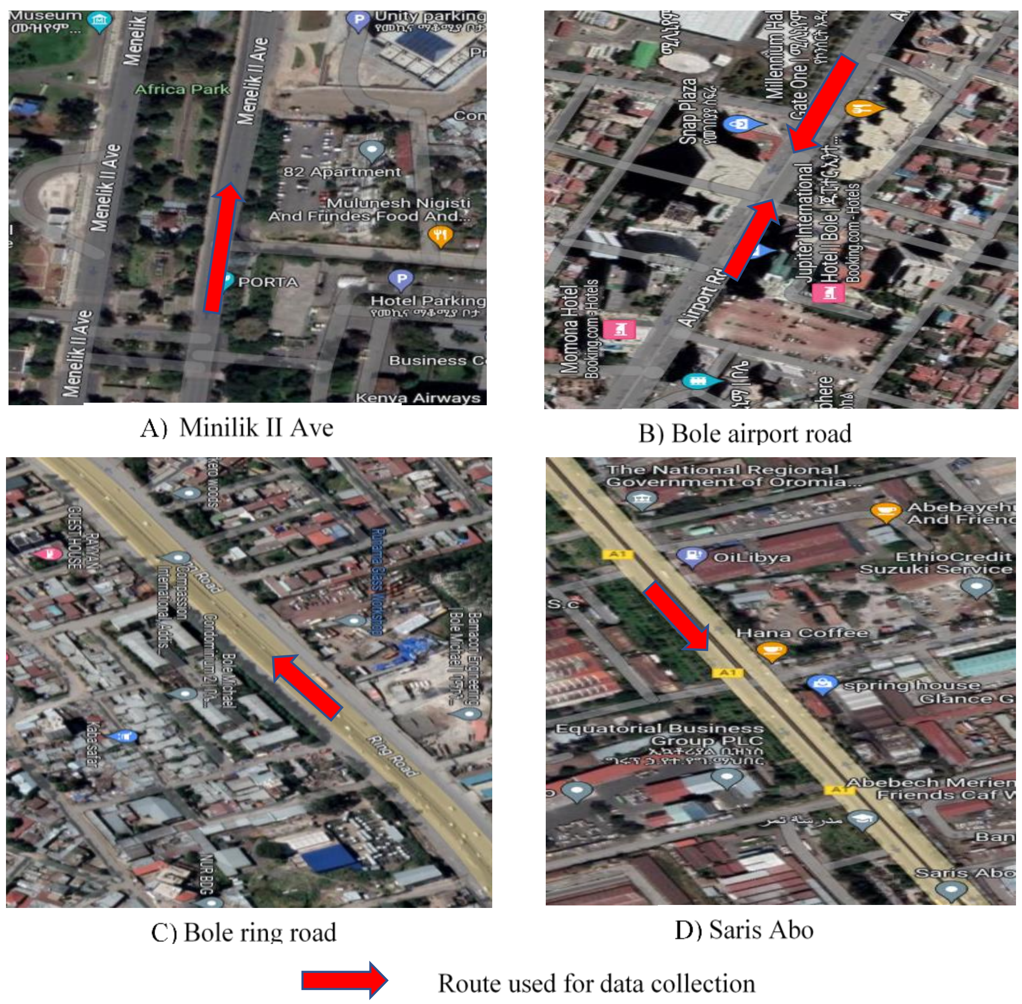


Figure 2: The four selected routes for data collection

2.2. Design of the experiment

In this study, an experiment was designed and executed using a full factorial design to determine how different levels of inputs affect outputs. This allows for systematically controlling for other variables while testing all combinations of inputs. The factors were vehicle speed at 10, 20, 30, 40 and 50 km/h and road slope of -2, 0, 2, 4 and 6 degrees with three repetitions (25 x 3 = 75 runs) at constant vehicle load, as shown in Table 1.

Table 1: Experimental design

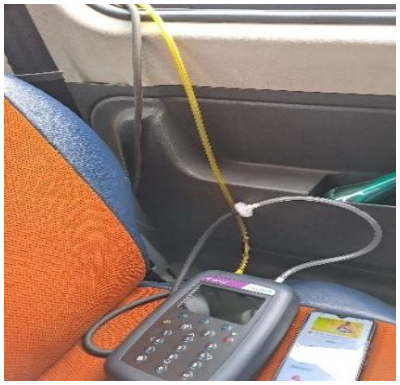
Factors	Levels				
	1	2	3	4	5
Vehicle speed (km/h)	10	20	30	40	50
Road slope (degree)	-2	0	2	4	6

The road slope and vehicle speed limit of Addis Ababa city were taken into account when choosing vehicle speed and road slope levels for this study. The levels of each factor were systematically varied to determine their effects on the tailpipe emissions of CO_2, CO and HC.

2.3. Data collection

In this study, a GA5000 model portable emissions tester manufactured by GeoTech was used to measure tailpipe emissions from gasoline and diesel vehicles. Figure 3 depicts its central unit with integrated sensors. The used gas analyzer measures the real-time concentrations of CO, CO_2 and HC; detailed specifications of the portable emission tester with its uncertainty are shown in Table 2. 3 mm outer diameter stainless steel probes with clamps were used to sample tailpipe emissions. There was an 8 m tube connecting the probe to the portable emissions.

a) Exhaust sampling line



b) Measuring device during the experiment

Figure 3: GA5000 portable gas analyser during the experiment

Table 2: Measured data with its measurement of uncertainty

Measured parameters	Instrument	Measurement type	Accuracy	$\bar{U}_{max}$ (%)
CO_2	GA5000 portable gas analyser	By dual wavelength infrared sensor with reference channel	±0.5% (vol)	3.82
CO		Internal electrochemical sensor	±2% (vol)	5.12
HC		Internal electrochemical sensor	±2% (vol)	2.91

The portable gas analyzer was mounted on the rear passenger seat at the start of each test, after which it was powered on and warmed up for 10 min. It had an internal battery that provided power, but it could be recharged using a 220 V alternative current power supply. On a full charge, the battery can provide 8 hr of uninterrupted power to the portable emissions analyzer. Additionally, GPS was used to collect the vehicle's speed and location data. The portable gas analyzer captured and saved the raw collected data on its internal memory and after installing its data logging software, the data was transmitted to the laptop using a USB cable. The data collected by GPS data was accessed through a web-based portal. Then the collected tailpipe emissions data was matched with vehicle speed and location data. Finally, the experimental data was structured and saved as an Excel file for additional processing in Minitab 21. In Table 3, details about both vehicles are given. The two vehicles were filled up with commercially available fuel from local fuel stations. Experiments were conducted from 07 to 11 June 2023 at an ambient temperature of 12 to 25 ºC. Tests were carried out on the chosen city roads in Addis Ababa.

The portable gas analyzer recorded the raw emissions data for HC, CO_2 and CO in percentage volume. In this study, tailpipe emissions in percentage volume were converted to g/km using a correlation developed by Pilusa et al. (2012). The unit conversion of tailpipe emissions of CO, CO_2 and HC are given in equations 1 to 3.

$$CO_2\left(\frac{g}{km}\right) = 166.3 \times CO_2\ (\%vol) \qquad (1)$$

$$CO\ \left(\frac{g}{km}\right) = 96.6 \times CO\ (\%vol) \qquad (2)$$

$$HC\ \left(\frac{g}{km}\right) = 57.1 \times HC\ (\%vol) \qquad (3)$$

2.4. Data analysis method

2.4.1 Full factorial analysis (FFA)

After converting the measured emissions unit to g/km, a full factorial analysis, which included the interaction analysis, Pareto chart of the standardized effect and regression analysis, was used. This enabled figuring out the most critical influencing factors of the emissions levels and how they interact. Additionally, it allowed evaluation of the accuracy of the model. Predictive models were developed using the conventional regression technique to ascertain the connection between input parameters and system output responses. The present study employed regression analysis to predict and evaluate the association between three performances attributes (CO_2, CO and HC) and the variables vehicle speed and road slope. Equation 4 gives the general linear regression model with multiple factors that was employed in this investigation.

$$Y = c + c_1\chi_1 + c_2\chi_2 + \ldots + c_{12}\chi_1\chi_2 + c_{13}\chi_1\chi_3 + \ldots + c_{11}\chi^2_1 + c_{22}\chi^2_2 + \ldots \qquad (4)$$

where: Y is the response, χ_1, χ_2, χ_3 … are the independent factors and c_1, c_2, c_{12}, c_{22}… are the cofficients of regression.

Table 3: The study's vehicle specifications

Parameters	Gasoline vehicle	Diesel vehicle
Vehicle manufacturer	Sokon Group	Toyota
Vehicle Model	DFSK Glory	Land cruiser
Model year	2016	2019
Engine capacity (CC)	1300	4164
Maximum power (kw)	112	96 @3800 rpm
Gross weight (kg)	2035	2720
Transmission	Manual	Manual
Mileage (km)	71446	90277
Fuel control strategy	Electronic fuel injection	Conventional type
Emission control	NA	NA

2.4.2 Desirability function analysis (DFA)

The DFA is a widely used optimization technique that values a set of responses and selects the variables that optimize the values of the responses (Abu Sheha et al., 2022). For the simultaneous optimization of multiple responses, in academics and industry the desirability function analysis method is frequently used (Devarajaiah & Muthumari, 2018; Thorisingam & Mustafa, 2022). Recently, Abu Sheha et al. (2022) used the DFA to find the risk factors with the lowest CO_2 emissions in Africa and Perec (2022) introduced the optimization of machining settings for high-pressure abrasive water jet cutting of Hardox 500 steel. The goal of the optimization procedure is to minimize, maximize, or reach a target value for the responses, y_i, using the desirability function d_i (y_i). Each value of y_i is assigned a score from 0 to 1, with 1 representing the most desirable value of y_i and 0 being the least desirable value of y_i (Devarajaiah & Muthumari, 2018). DFA relies on a function called composite desirability to convert many response qualities into a single response function (Perec, 2022). Using DFA, this study simultaneously reduced CO_2, CO and HC emissions. To arrive at a solution, the analysis was carried out in the subsequent steps.

1. Determination of desirability index

As the main objective of this study was to minimize CO_2, CO and HC to the smallest possible value. Consequently, the study's findings ought to be applied to determine the best operating range for lowering emissions. When the output response takes the smallest possible value, the factor di is calculated as equation 5 (Abu Sheha et al., 2022; Devarajaiah & Muthumari, 2018; Perec, 2022).

$$d_i = \begin{cases} 1, y_i \leq y_{min} \\ \left(\frac{y_i - y_{max}}{y_{min} - y_{max}}\right)^r, y_{min} \leq y_i \leq y_{max}, r \geq 0 \\ 0, y_i \geq y_{min} \end{cases} \quad (5)$$

where: d_i is the individual desirability, y_i is the expected value, y_{min} is the lower tolerance limit, y_{max} is the upper tolerance limit and r is the weight.

2. Determination of composite desirability

The overall desirability function (D) was calculated by combining the individual desirability index values of each response into a single value using equation 6.

$$D = \sqrt[w]{d_1^{w1} \times d_2^{w2} \dots d_i^{wi}} \quad (6)$$

where: D is the overall desirability, d_i is individual desirability, w_i is the weight of the response y_i, and w is the sum of the individual weights.

3. Choice of the optimum level responses and their combination

Lastly, the best combination of level control settings works were figured out. The high composite desirability value suggests a low emissions level.

3. Results and Discussion

The data collected for each run included three repetitions and the average values were taken for further analysis. Four passengers (275 kg) were loaded into the vehicles when data were collected from gasoline and diesel vehicles.

3.1. Full factorial analysis

3.1.1 General factorial regression for CO_2

Figures 4 and 5 display the interaction plot of CO_2 emissions rate for various road grade of gasoline and diesel vehicles. In general, the average rate of CO_2 emissions rises noticeably as road gradient increases. The CO_2 emissions rates for road gradients of 2, 4 and 6 deg were 16.25, 28.58 and 43.36 %, respectively higher than the emission rates of level road for gasoline vehicles (Figure 4). This study found that the lowest CO_2 was achieved in a gasoline powered vehicle at speeds between 30 and 40 km/h. This is because at these speeds, the gasoline engine is running more efficiently with lower fuel consumption and its CO_2 emissions are lower.

For diesel vehicles, the CO_2 emissions rate for road gradients of 2, 4 and 6 deg were 53.7, 91.08 and 245.85 %, respectively higher than the emission rates of level road, and 36 % reduction in CO_2 was observed in downhill of -2 deg (Figure 5). According to this study, a diesel vehicle travelling between 20 and 30 km/h produced the least amount of CO_2. This is due to the diesel engine's increased efficiency at these speeds, which results in reduced CO_2 and fuel consumption. These changes were observed due to the CO_2 emissions rate having a strong correlation with fuel consumption (Meng et al., 2023).

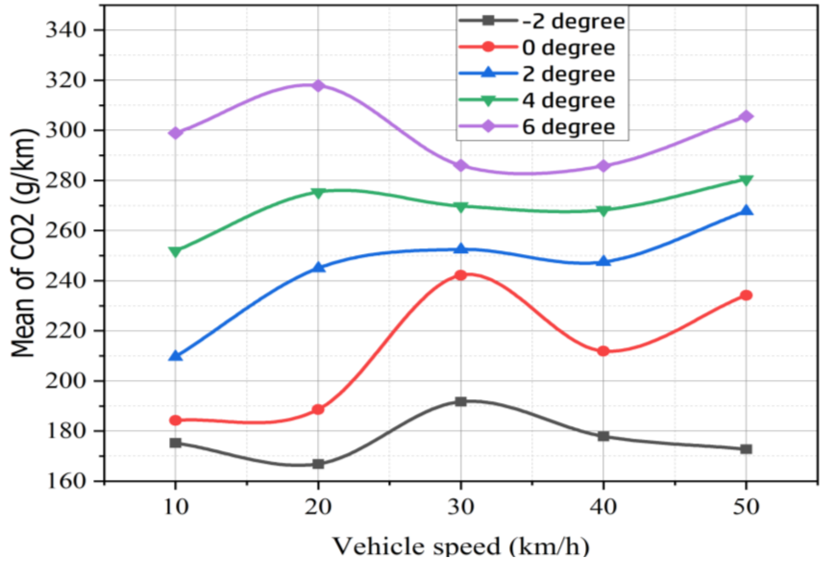


Figure 4: CO_2 interaction plot for SI engine operated vehicles

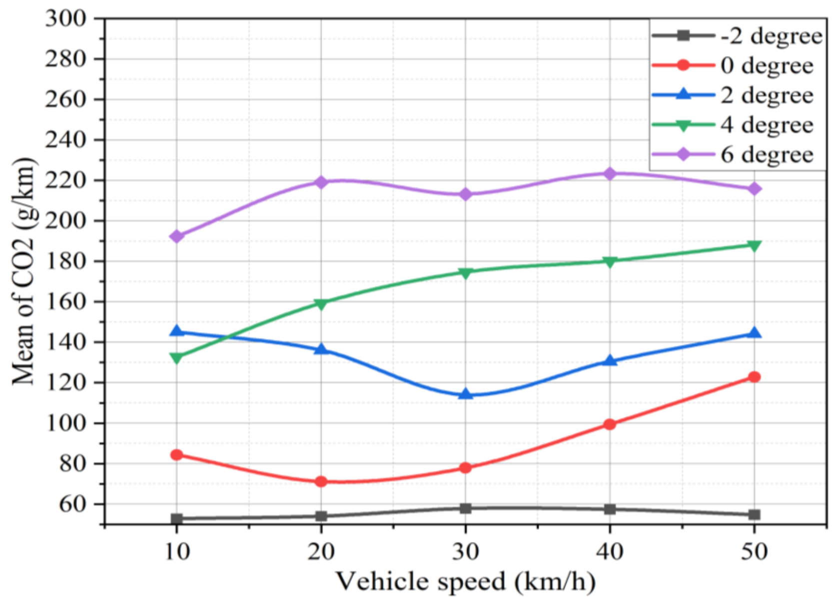


Figure 5: CO_2 interaction plot for diesel engine operated vehicle

On routes with positive road grades, the vehicle requires more power, which results in increasing fuel consumption and CO_2 emissions. An engine's CO_2 emissions are influenced by the oxygen in the combustion chamber and its temperature (Gopal et al., 2014).

According to this study, on a downhill (-2 degree) and level road gasoline vehicles emit highest CO_2 while travelling at 30 km/h (Figure 4). This shows that in downhill driving at 30 km/h at a -2 degree and level road, the engine operated at a lower RPM, which led to a higher emission of CO_2. Nevertheless, when the vehicle speed is less than 30 km, the engine RPM should be near idle, lowering CO_2 and fuel consumption at lower speeds. With increasing vehicle speed beyond 30 km/h at -2 degrees and on level roads, CO_2 production is decreased due to increased engine RPM, which results in better engine efficiency.

With a 95% confidence level, regression analysis was performed using the Minitab 21. For CO_2 of gasoline and diesel vehicles, the fitted regression models are provided in equations 7 and 8, respectively.

$$CO_2(g/km) = 189.77 + 0.682 \times V + 16.89 \times G - 0.0615 \times V \times G \quad (7)$$

$$CO_2(g/km) = 79.1 + 0.461 \times V + 17.82 \times G - 0.0571 \times V \times G \quad (8)$$

where V is vehicle speed in km/h, and G is road slope in degree.

The degree to which the regression model helps with variability explanation is indicated by the R-square (R-sq). R-sq values near 1 indicated that the regression model adequately explains the majority of the dependent variables. The values of R-sq and adjusted R-sq of Table 4 show that the accuracy and precision of the model results were best for both gasoline and diesel vehicles. Based on these results, it can be concluded that the regression models developed for gasoline and diesel vehicles are reliable to estimate CO_2.

At a 95% confidence interval, both vehicle speed and road slope crossed the red dotted line in the Pareto chart of Figure 6 for both gasoline and diesel vehicles, indicating that both variables are significant for determining CO_2 emissions. Additionally, for CO_2 determination, the Pareto chart showed that road slope has a greater effect than vehicle speed. Thus, neglecting the road slope will result in incorrect estimation of vehicle CO_2 emissions.

Table 4: Model Summary for CO_2, CO and HC

Emissions	**Vehicle**	**R-sq (%)**	**R-sq (adj) (%)**	**R-sq (pred) (%)**
CO_2	Gasoline	99.98	99.97	99.96
	Diesel	96.03	95.47	94.48
CO	Gasoline	99.89	99.84	99.76
	Diesel	85.91	83.9	76.15
HC	Gasoline	96.65	95.04	92.46
	Diesel	73.12	72.57	70.63

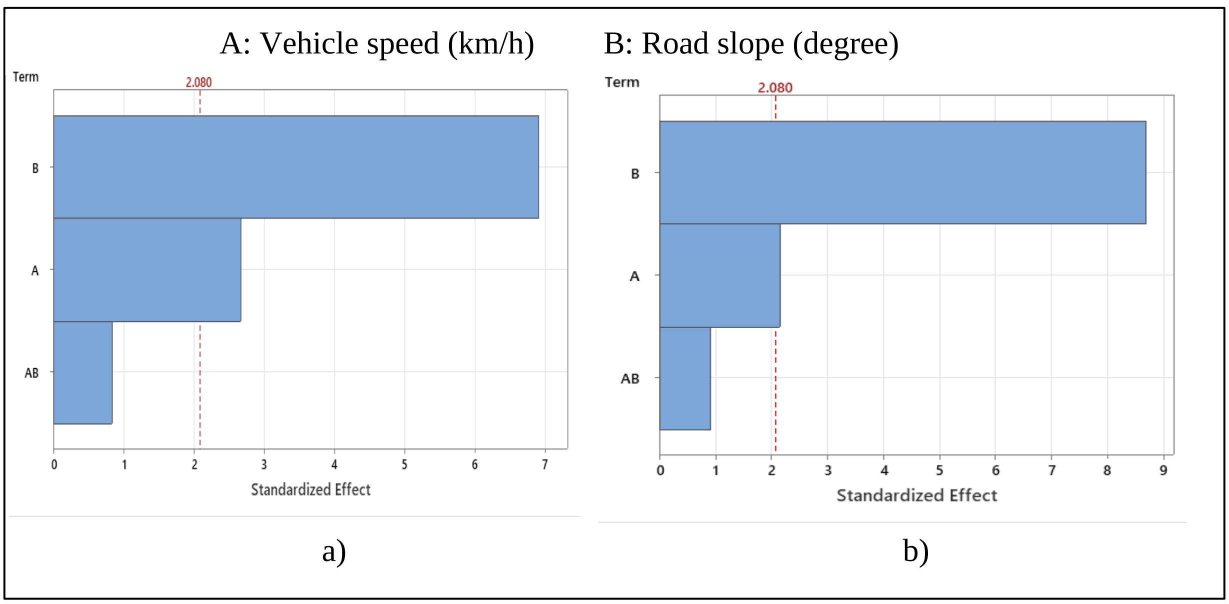


Figure 6: Pareto chart of the standardized effects of CO2 a) SI vehicle b) CI vehicle

3.1.2 General factorial regression for CO

The main and interaction effect of CO emissions rate for different road grades for gasoline and diesel cars is shown in Figures 7 and 8. The average rate of CO emissions generally rises noticeably with an increase in road gradient and declines with an increase in vehicle speed. For petrol vehicles, the CO emissions rate for roads with gradients of 2, 4, and 6 degrees were respectively 37.76, 168.47 and 177.1 % higher than the emission rates for roads with a level surface, and a reduction of 10.27 % was seen when driving downhill at a -2 degree angle (Figure 7).

For diesel vehicles, the CO emissions rates for roads with gradients of 2, 4, and 6 degrees were, respectively, 42.84, 76.48 and 104 % higher than the emission rates of a level road, and an 8.9 % CO reduction was seen on downhill roads of -2 degrees (Figure 8).

Equations 9 and 10 provide the fitted regression models for CO emissions from gasoline and diesel vehicles, respectively. The value of R-sq and adjusted R-sq are displayed in Table 4, indicating both regression models of gasoline and diesel vehicles had the highest levels of accuracy and precision in the findings.

$$CO\ (g/km) = 77.83 + 1.224 \times V + 5.49 \times G - 0.0453 \times V \times G \quad (9)$$

$$CO\ (g/km) = 68.48 + 1.075 \times V + 5.38 \times G - 0.0367 \times V \times G \quad (10)$$

where V is vehicle speed in km/h, and G is road slope in degree.

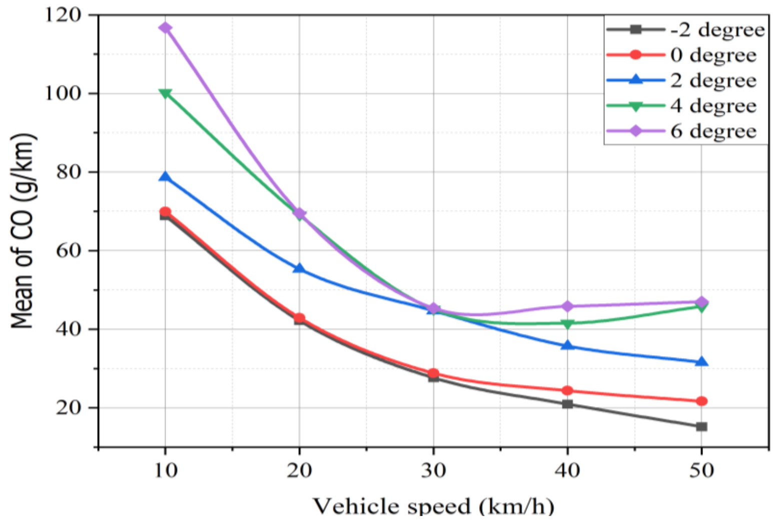


Figure 7: CO interaction plot for SI engine operated vehicles

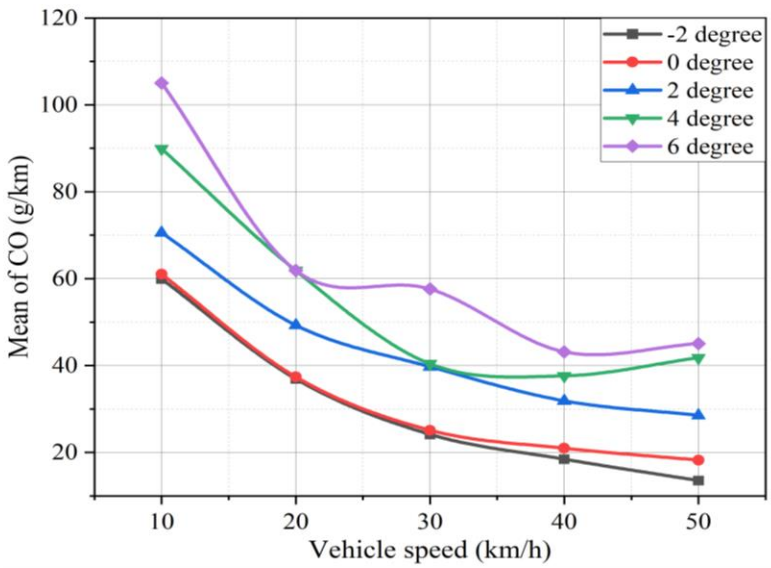


Figure 8: CO interaction plot for diesel engine operated vehicle

For both gasoline and diesel vehicles, the Pareto chart shown in Figure 9 showed that both speed and road slope passed the red dotted line at a 95% confidence range, demonstrating that both variables are relevant for predicting CO emissions. Therefore, ignoring the road gradient will again lead to inaccurate vehicle CO emission estimation. The developed regression models are reliable to project the CO emission from gasoline and diesel vehicles.

3.1.3 General factorial regression for HC

The HC emissions rate for different road grades for gasoline and diesel cars are shown in Figures 10 and 11. Lower HC emissions rates were seen at 30 km/h for both gasoline and diesel vehicles. In the case of gasoline vehicles, the HC emissions rate showed a decreasing trend as the road slope increased from the level road to 4-degree angles, but peak HC was observed at a 6-degree road slope. As the road slope increased from -2 to 4-degree angles, the rate of HC emissions increased for diesel vehicles, but as the road slope increased further, the rate of HC emissions decreased. The greater engine load, which lowers the amount of HC emissions, is probably the reason for the decrease in HC emissions rate for petrol vehicles at higher angles. On the other hand, for diesel vehicles, the rise in HC emissions rate at a lower angle is probably caused by the reduced engine load, which prevents the engine from reaching its ideal combustion temperature, resulting in incomplete combustion and increased HC emissions.

When driving on a level surface, petrol vehicles' HC emissions rates on roads with gradients of -2, 2, and 4 degrees did not differ significantly from the level road, whereas traveling uphill at a 6-degree angle caused the HC emissions to increase by 27%. While diesel vehicles' HC emissions rate on roads with gradients of -2 and 2 degrees did not differ significantly compared with level roads, HC increased by 20.83 and 13.44 % on 4 and 6 degree uphill routes, respectively. Figures 10 and 11 showed that there is no a steady correlation between HC emission and speed. An observation similar to this was made by Bokare & Maurya (2013). Nevertheless, unique characteristics were attained for HC emission at 20 km/h on a slope of 6 degrees, this occurred as a result of the higher incomplete process, and employing a lower gear at this driving speed and the road slope.

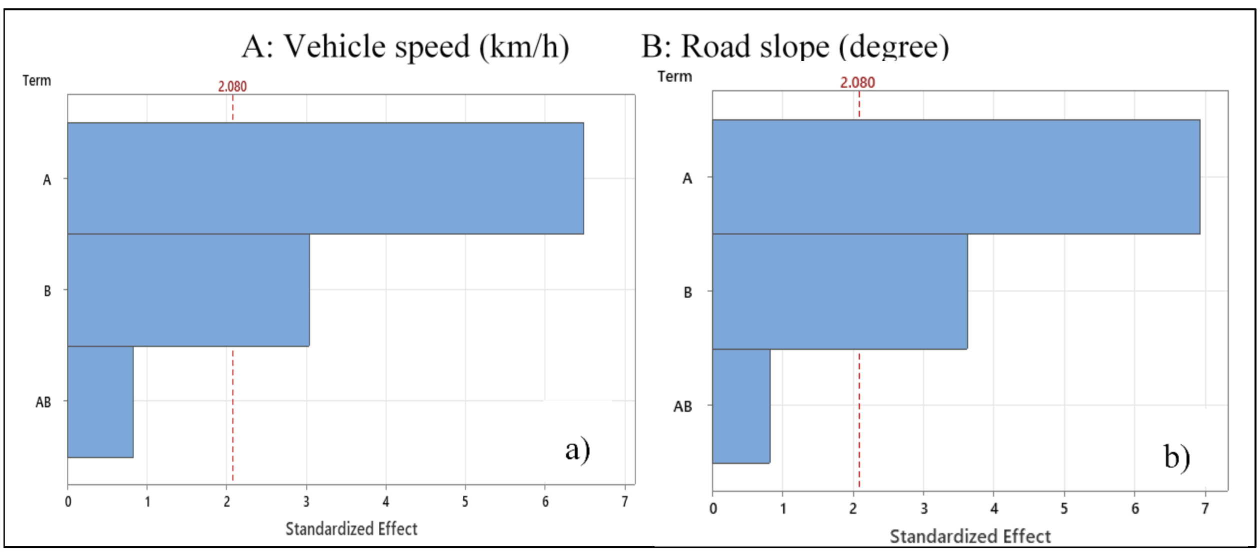


Figure 9: Pareto chart of the standardized effects of CO: a) SI vehicle b) CI vehicle

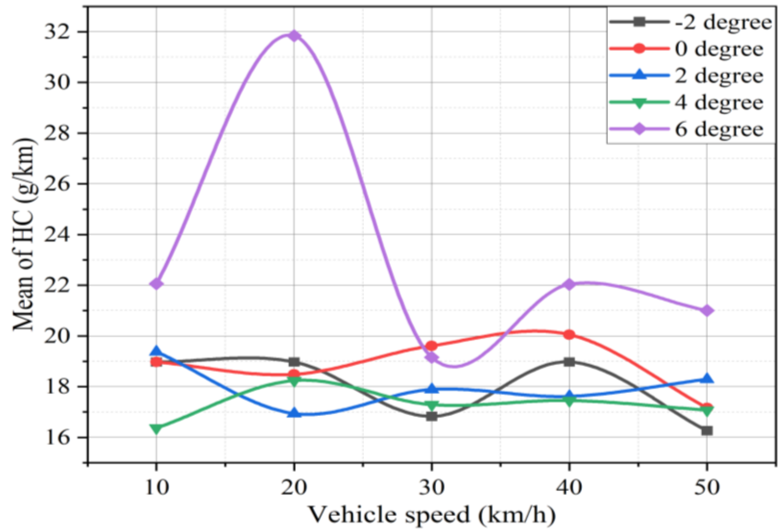


Figure 10: HC interaction plot for SI engine operated vehicle

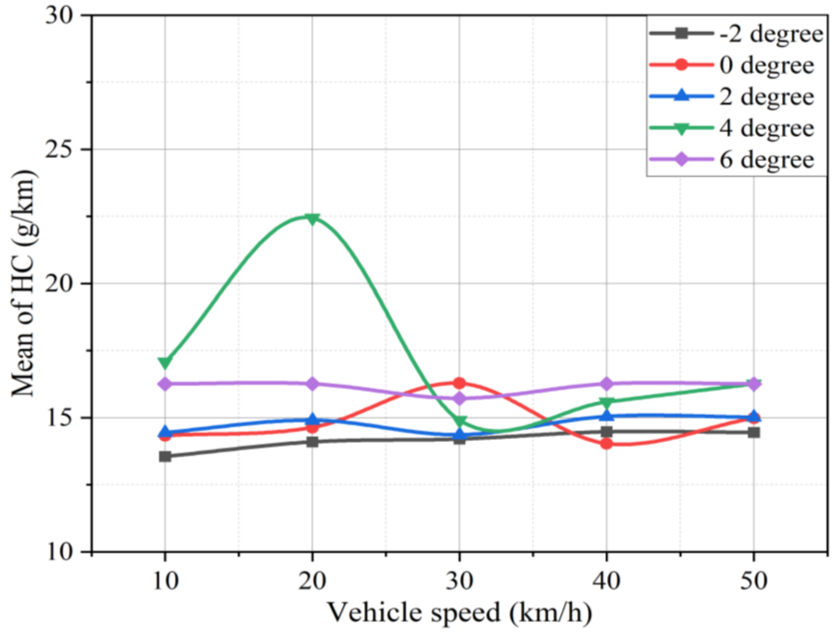


Figure 11: HC interaction plot for diesel engine operated vehicle

The fitted regression model of HC emissions for gasoline and diesel is shown in equations 11 and 12. As shown in Table 4, R-sq and adjusted R-sq for gasoline and diesel vehicles had the high levels of accuracy and precision.

$$HC\ (g/km) = 19.09 + 0.0302 \times V + 0.598 \times G - 0.00052 \times V \times G \quad (11)$$

$$HC\ (g/km) = 14.647 + 0.0049 \times V + 0.523 \times G - 0.00676 \times V \times G \quad (12)$$

where V is vehicle speed in km/h, and G is road slope in degree.

3.2. Desirability functionality analysis (DFA)

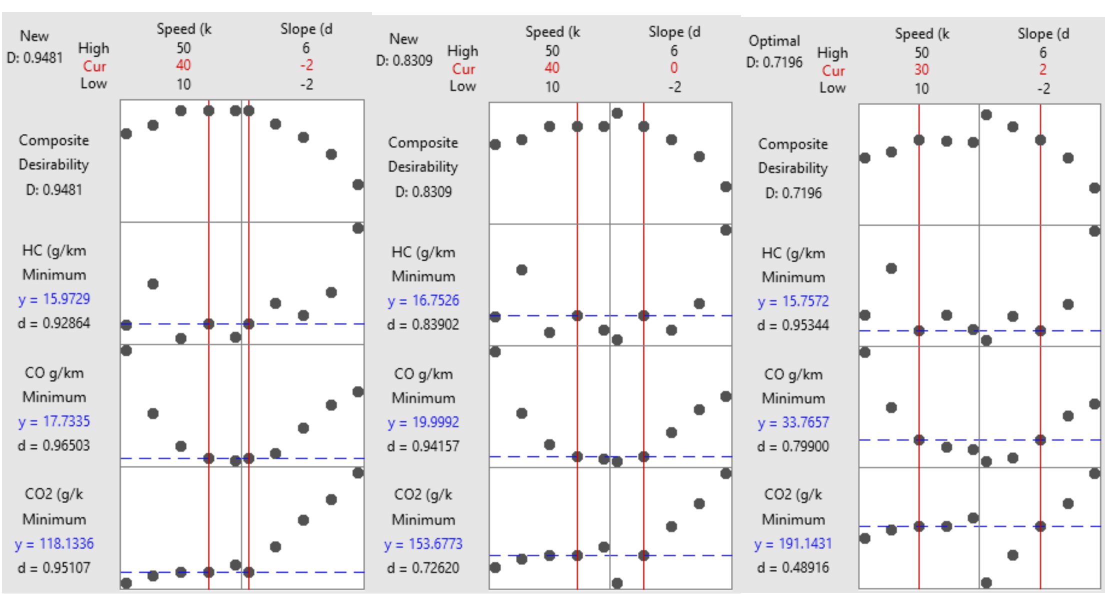
The DFA was conducted to identify best points that minimize CO, HC, and CO_2 formation on urban routes. The solutions were obtained from a variety of tests conducted on different road slopes and vehicle speeds of the selected gasoline and diesel vehicles. Table 5 displayed the top three obtained solutions for each road slope.

According to Table 5 and Figure 12 (a), at -2 degree slopes, 40, 50, and 30 km/h have almost equal composite desirability indexes of 0.948. This indicated that the composite desirability is not affected by speed and the downslope of the road. As shown in Table 5 and

Figure 12 (b), on level roads, 40, 30 and 50 km/h have composite desirability indexes of 0.831, 0.827, and 0.821, respectively. The composite desirability index is also found to be highest at 40 km/h, which is the best speed for minimizing CO, HC, and CO_2 emissions on level roads. This speed lets vehicles move along the level road at a speed that is neither too fast nor too slow, allowing them to get the most efficient fuel usage. As a result, emissions of CO_2, CO, and HC were simultaneously decreased.

Table 5: Solutions of the desirability function analysis

S/N	Speed (km/h)	Slope (deg)	Average HC (g/km)	Average CO (g/km)	Average CO_2 (g/km)	Composite Desirability
1	40	-2	15.445	23.549	117.892	0.948
2	50	-2	15.973	17.734	118.134	0.948
3	30	-2	15.497	16.518	128.587	0.948
4	40	0	16.753	19.999	153.677	0.831
5	30	0	16.225	25.815	153.436	0.827
6	50	0	16.276	18.784	164.13	0.821
7	30	2	15.757	33.765	191.143	0.720
8	40	2	16.285	31.550	191.224	0.709
9	50	2	15.808	30.334	201.678	0.694
10	40	4	17.165	42.283	220.085	0.556
11	30	4	16.638	48.098	219.844	0.555
12	50	4	16.689	41.067	230.538	0.528
13	30	6	19.055	54.492	257.58	0.285
14	40	6	19.583	48.676	257.821	0.281
15	20	6	21.111	69.268	252.954	0.243



a) -2 degree road slopes b) Level road c) +2 degree road slopes

Figure 12: Plots illustrating DFA's responses

The composite desirability indexes for 30, 40 and 50 km/h at 2-degree road slopes were 0.72, 0.709, and 0.694, respectively. The most desirable speed for minimizing CO, HC, and CO_2 emissions on 2-degree road slope was 30 km/h (Figure 12 (c)). Additionally, it confirms the effectiveness of speed limits in mitigating environmental damage. The top three composite desirability indexes for roads with 4 and 6-degree slopes were all less than 0.7. When compared to other road slopes, the outcome was not significant. Roads with these degree of slope were therefore undesirable for determining the best vehicle speed for their operation. Therefore, it is advisable not to limit the driving speed of vehicles on such slopes, in order to reduce emissions.

4. Conclusions and Recommendations

Based on the experimental data obtained using a portable emissions analyzer, the effects of vehicle speed and road slope on tailpipe emissions were investigated using a full factorial design of the experiment. For the selected vehicle speeds and road slopes, this investigation aimed to determine the best speed to minimize CO_2, HC, and CO emissions simultaneously. The best combination of speed and slope was found to reduce emissions in this study using desirability function analysis. The emissions trend from two passenger vehicles on a specific path road with variable road gradients and vehicle speeds were assessed.

For gasoline vehicles, CO_2 emissions from roads with road slopes of 2, 4, and 6 degrees were 16.25, 28.58, and 43.36 % higher than those from level roads. Diesel vehicles emit 53.7, 91.08 and 245.85 % more CO_2 during gradients of 2, 4, and 6 degrees compared to a level road, and 36% less CO_2 during gradients of -2 deg. Further, the Pareto chart showed that road slope has more impact on CO_2 determination than vehicle speed. CO emissions generally rise with increasing road slope and decline with increasing vehicle speed. Gasoline and diesel vehicles both emitted lower amounts of HC when traveling at 30 km/h. According to the composite desirability index, the best speed to simultaneously minimize CO, HC, and CO_2 emissions was found at 30 km/h for a 2-degree road slope and 40 km/h for level roads. In light of this, 30, 40, and 50 km/h have almost equal composite desirability indexes of 0.948 for -2 degrees road slope. The results of this study lead to the recommendation that speed limits in metropolitan areas be established with consideration for CO_2, HC, and CO emissions in order to minimize them simultaneously.

Overall, when designing roads and establishing speed limits in urban settings, emissions need to be considered. This can improve public health as well as contribute in the reduction of air pollution. The findings of this study could contribute to a more sustainable transport system, with the potential to reduce emissions from vehicles significantly. The relationship among vehicle speed, road slope, and tailpipe emissions could be studied further by detailed studies involving different types of vehicles and emissions control devices. In addition, higher vehicle speeds, higher road gradients, weather conditions, mileage, and different vehicle loads need to be considered in further research. Furthermore, this study can be extended by considering factors such as NO_X, PM, and various fuel types.

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