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Modelling Vehicle Emissions and Fuel Consumption Based on Instantaneous Speed and Acceleration Levels

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Abstract

Transportation pollutants affect air quality and result in climate changes. This study aims to develop emission and fuel consumption models. The study was undertaken in Greater Cairo Region where congestion episodes such as acceleration and deceleration are the most vehicle operating modes. The available data were obtained from Egyptian Environmental Affairs Agency for different types of fuel that include; Diesel, Gasoline and Natural Gas. Second-by-second data points were collected using an on-board emission measurement system. The data include fuel consumption and emission rates for nine vehicles.The final models are used to predict values of nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2) and fuel consumption (FC).The predicted fuel consumption and emissions models were found to be accurate with (R2) ranging from 0.70 to 0.95.The study alsodemonstrated that emissions and fuel consumption are more sensitive to the acceleration than to speed. Furthermore, deceleration activities reduce the emission of vehicles.

Keywords : Emission modelling, Fuel consumption, Acceleration, Deceleration, Tailpipe.

1. Introduction

Climate change due to greenhouse gases (GHGs) and their negative impacts haveraised the global attention. There were many attempts to study the emission contribution for each industry [1]. Transport sector itself consumes a lot of fuel and therefore contributes a great shareofharmful gases. In Egypt, carbon dioxide (CO2) is the most common gas emitted from the moving sources. Carbon dioxideamount ranges between 25.0 % to 30.0% of the total Egypt GHG amount. Other minorGHG such as nitrous oxide (N2O)is also emitted from different transport resources.Private and public transportationfleet consist of many types such as private cars, taxis, minibuses and buses. The number of registered private vehicles in Egypt isincreasing at a very high rate. This situation produces huge increasing in the fuel consumption and consequently increasing in GHG emission. Climate change convention[1] demonstrated that emissions by transport modesareabout 22.50%of the total GHG emission. World Bank (WB) report indicated that 19,200 people died and over three billion days were lived with diseases in year 2017 as a result of air pollutions [2]. In 2018, Central Agency for Public Mobilization and Statistics indicted that the fuel consumption is about 79.00 million tons in 2017 with an annual increase by amount of 4.20% [3].

It is necessary to develop fuel consumption and emission modelsthat take in consideration the episodic modes of vehicles that occur in Egypt streets. These models are essential to quantify the impact of the national fleet on air quality and fuel consumption. In order to develop models that consider the national circumstances, this study is based on real world second-by-second emission data collected from vehicles inside Greater Cairo Region (GCR). The models considered emissions produced from Diesel, Gasolineand Natural Gas.The models can estimate the fuel consumption and GHG emissions as a function of the real-world modes including speed, acceleration and deceleration.Therefore, these models considered traffic and driverimpacton emission rates.

2. LITERATURE REVIEW

There are several approaches to develop models to predict emission and fuel consumptions. Some of these approachesare based only on average speed.Another approach depends on developing emission maps based on speed and engine power. Emission map relatesthe average emission rate with combination of speed and acceleration in the driving cycle. In this approach, second-by-second emission test isimplemented at many engines operation points and takesthe average of readings [4]. This approach is considered expensive and a time consuming.The deficiency in emission map procedure isthat it is based on the engine steadystate that is ignoringthe episodic nature of vehiclemovement in congested street like the case of GCR streets. The expected errorsin emission map are generated when using the interpolation in the emission map gridto compute an average emission value [5,6].On the other hand, models that are based on regression method manipulate the instantaneous speed, acceleration and deceleration as independent variables. These models overcome some deficiencies of the other emission models. Besides, the models developed by regression functions could be used in micro scale and macro scale operation modes. When second-by-second speed profilesare available, the regression modelscan estimate the highly time emission data and fuel consumption. If the average speed is given, the model is still working well to compute the required information. Wang et al. [7]used speed and acceleration as inputs for NOxemission model. They simulated traffic data from freeways for about 15 hrs. to 19 hrs. to get trajectory, acceleration and location. They noticed that emissions ratesexhibited a wide variation in its value with change in speedlevels. They concluded that emissionsestimation should include the acceleration levelsinstead of using only the average speed. Also, they noted that the effect of acceleration levels on emission values is higher on low speed. When they applied the correction factors for the acceleration, the NOx emission values showed an increase by 34.0 %.Ahn et al. [8]studied shortcoming from emission models that only used the average speed and ignoredusing thevariation in speed and acceleration levels. Therefore, they collected data from site and dynamometer for modelling emission and fuel consumptionas a function of instantaneous acceleration and speed. Their models presented better prediction for fuel consumption and emission rates.

Rakha et al. [9]proved that the microscopic models could be applied for field and simulated emission and fuel data. They studiedthe field data that were observedby Oak Ridge National Lab (ORNL). Their studiesproved that vehicle emissions and fuel consumption are sensitive to the combined effect of acceleration and speed. Furthermore, their study showed that the use of modelsbased only on the average speed failed to consider the impact of important factors on emission rates.Ding et al. [10]declared that speed and acceleration were two importantvariables for estimating emission rates and fuel consumption. These two variables account for 62.0 % and 90.0 % of the squared error (R2) for all measures of effectiveness (MOEs). The study demonstrated that the speed, speed squared, number of stops, acceleration, and kinetic energy are vital variables to predict emission rates and fuel consumption. Their regression models were found to predict fuel consumption and emission rates of HC, CO, and NOx to within 0.90 to 0.96 of the microscopic emission estimates. Furthermore, the model estimates fall within the margin of variability of the typical normal vehicles in the US.

Another study illustratedthat values of HC, CO and NOx are sensitive to vehicle speed at the same acceleration level. This study demonstrated that the emission rates initially decrease with the increase in the speed and then increase afterwards with further increase in speed at the same acceleration level. The emission rates are also found to increase with the increase in the acceleration levels[11].Sharma et al.[12] developed emission models in the form of second-degree polynomial using speed as an independent variable. They tested vehiclesnamely; a car, a SUV, and a truck. The emission models for these three types of vehicles and for CO_2, CO, HC and NOXpollutants are developed. The speed value and the emission ratesdisplayed a strong correlation. This correlation was found satisfactory by considering experimental errors with R^2 between 0.30for CO to 0.95 for CO_2.

Rakha et al. [13] compared the macroscopic models and the microscopic models for emission rates. In macroscopic models, emission rate is expressed as a function of the average speed that is estimated from a limited number of standard cycles. They stated that the microscopic model overcomes the insufficiency of macroscopic models. They considered that the microscopic models are more precise for predicting the emission and the fuel consumption because it uses real speed and acceleration profiles. In these models, the second-by-second output are accumulated to predict the consumed fuel and the emission rates.

Authors concluded from the literature review that the vehicle emissions and fuel consumption can be computed accurately by implementing the modelsfrom real world on-board emission measurement data rather than using dynamometer data to consider the effect of the different operation modes. The literature review also demonstrated that speed and acceleration are vital variables for accurate emission and fuel consumption estimation.Simultaneously, second-by-second speed profiles are essential to illustrate the actual vehicle operation modes.

3. PROBLEM DESCRIPTION

The objective of this paper is to develop speed and acceleration dependent emission models. For this purpose, the test vehicles ran at different speed ranges for different segment of streets. These vehicles typically consume three types of fuel that are commonly used in Egypt. Nine representative vehicles were considered to collect measurements using the on-board instruments. The study considered the effect of speed, acceleration and deceleration because several planning studies were done at macro-level that ignore the effect of traffic and driver behaviors. SPSS software and regression equations were used to build the required models. The following paragraphs explain the proposed methodology in details.

Figure 1 shows the general methodology steps to develop models for emission and fuel consumption from Egyptian Environmental Affairs Agency (EEAA) data.

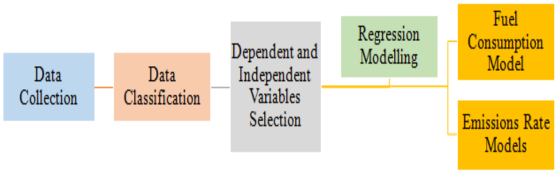


FIGURE 1. Proposed methodology to develop the models

3.1 On-Board Data Collection and Classification

The first step is to collect on-board second-by-second emissions data from a sample of vehicles thatpresent the national fleet.The on-board data reflects the real driving situations. That data can facilitate the development of micro-scale emission models. For this reason, a huge amount of data sets was collected to reflect the vehicle emissions and their activities. These data were analyzed and tested to determine the best procedure to best fit the data to develop comprehensive emission models.The field records were collected bythe Egyptian Environmental Affairs Agency (EEAA) in Greater Cairoin 2017 forninevehicles. The sample of nine vehicles included three vehicles working with diesel fuel, three vehicles working with gasoline fuel and three vehicles working with natural gas fuel. These nine vehicles are well representative of the engine’s technology in the national fleet. The test vehicles were produced between 1990 and 2015.These vehicles were selected in order to produce an average vehicle in terms of engine technology, weight, model year and vehicle type.The number of collected data points ranged from 3,800 to 16,500 for each vehicle.The nine vehicles were classified to three groupsaccording to the fuel type. The first group was for vehicles that working with diesel, while the second group was for vehicles that working with natural gas and the last group for vehicles that working with gasoline. In order to represent thevehicle fleet, three hypothetical composite vehicles were created. The composite vehicles were derived as an average vehicle to reflect three typical vehicles.The on-board data collection process used two instruments. One instrument measured the speed profile and the other instrument measuredthe emission. Global Positioning System (GPS) was used to record the vehicle location and speed while the gas analyzer was used to collectthe emission rates. Second-by-second records of nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2) and fuel consumption (FC)werecollected. Readings of 79,272 exhaust points were recorded for the nine vehicles. The field measurements included records along local, collector, arterial streets.

3.2 Dependent and Independent Variable Selection

There are many variables that affect the vehicle fuel consumption and emission rates. These variables are related to the followings; travel, weather, vehicle, roadway, traffic and driverrelated factors. The travel factors account for the distance and number of trips traveled in the analysis period. The weather factors account for temperature, humidity, and wind effects. The vehicle factors account for several variables including the engine size, the condition of the engine, the air conditioning and the soak time of the engine. The roadfactors account for the road grade and surface condition. The traffic factors account for vehicletovehicle andvehiclecontrol interaction. Finally, the driver factors account for differences in driver behavior.Ding et al. [10] demonstrated that using the average speed only is insufficient for accurate estimation of the vehicle emission. Theysuggested models that are consistent with microscopic fuel and emission model. These modelsimplemented the vehicle instantaneous speed and acceleration to estimate the estimation rates.Rakha et al. [13]indicated that the fuel consumption rate is more sensitive to cruisespeed levels than to vehicle stops. The vehicle stops that occurredduring the different acceleration levels have a significant impact on vehicle emission rates. They found that carbon monoxide (CO) and hydrocarbon (HC) emission rates are very sensitive to the level of acceleration when compared to the running speeds in the range of 10 km/h to 120 km/h. The impact of the deceleration levels on the MOEs was relatively small when compared with the other factors in their study. Also, the study demonstrated that the increase in speed limit could have extremely negative environmental impacts. The increase in the speed limit from 90.0 km/h to 106 km/h may result in 60.0 % increase in HC emission, 40.0 % increase in NOx and 80.0 % increase in CO emissions.

In Egypt, most emission and fuel consumption models studied the impact of road, weather, and vehicle factors on vehicle emissions. Also, thecurrent models use the average speed and the traveledlength to estimate the emission and fuel consumption. Therefore, these models can't capture the impact of traffic and driver factors on vehicle emissions. It can't be used to evaluate the improvement in traffic projectin the before-and-after scenarios. The analysis of the collected measurements in Greater Cairo demonstrated that most vehicles are traveling in continuous acceleration and deceleration modesbased on analysis and speed profile illustrated in Fig. 2. The literature review reveals that speed and acceleration have the significant impacts on emission rates [8, 11].The massive amounts of on-board measurements were further analyzed. Differences in vehicle location with time were used to calculate the vehicle speed.While, differences in the vehicle speed with time were used to calculate deceleration and acceleration. The fuel consumption and emission rates measurements were provided for a range of speeds from 0.0 to 70.0 km/h and for a range of accelerations from −2.0 m/s2 to 3.0 m/s2. These data can simulate the typical traffic conditions in Cairo Region that include deceleration, idle time and acceleration. Similar values were used by Ahn et al. [8] and Rakha et al. [13].

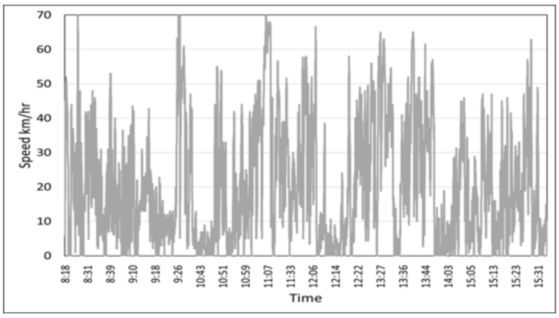


FIGURE 2. Vehicle speed profile

3.3 Modeling Fuel Consumption and Emission Data

Regression models and SPSS software were used to build the fuel and emission models. First, comprehensive literature review was conducted to obtain a general idea about the models that best fit fuel and emission data. Several regression equations were investigated as part of the study to choose the model that fit the data collected by EEAA. Second, on-board speed measurements were used to derive the acceleration and deceleration. At the end, linear, quadratic and cubic terms of speed and acceleration were evaluated. In these models, emissions and fuel consumptions were the dependent variables and instantaneous speed and acceleration were the independent variable. The data was fitted and validated by obtaining various goodness of fit. Coefficients, intercepts were extracted for these models. The integrated models can be expressed as shown in Equations (1) and (2). The final models included third-degree polynomial equations that follow the form of Equation (1). The correlation

among the various functions for the variables were found
satisfactory by investigating the experimental errors (R-square). Tables from 1 to 3 provide the summary for all coefficients and intercepts values.

The models produced reasonable correlation coefficients and relatively good fit to EEAA data. The produced models fit diesel, gasoline and natural gas data with (R-square) between 0.70 to 0.95. Except for CO emission, the data related to natural gas were not enough to produced reasonable correlation coefficients. It was expected that using speed and acceleration terms as independent variables will result in multi-collinearity because of the dependency of both these variables. To reduce the effect of multi-collinearity, some of the regression terms were removed as shown in Tables from 1 to 3. Furthermore, the models produced some negative coefficients and intercepts values. Therefore, further evaluations were considered to develop better models. Data transformation technique was adopted to solve this problem. In this technique, the variables were transformed using the natural logarithm function as shown in Equation (2). Then, regression models were fitted to the transformed data. Finally, the computed values were then transformed back by using the exponential function.

$$MOE = C + \sum_{i=0}^{3} \sum_{j=0}^{3} \left(f_{ij} * s^{i} * a^{j}\right) \quad (1)$$

$$\ln\,(MOE) = C + \sum_{i=0}^{3} \sum_{j=0}^{3} \left(f_{ij} * s^{i} * a^{j}\right) \quad (2)$$

Where:
MOE: fuel consumption or emissions rate (mg/s)
C: intercept*f*: regression model coefficient
s: speed (m/s)*a*: acceleration (m/s^2)

4. RESULTS

Tables from 1 to 3 provide the summary for all coefficients and intercepts values that were produced based on Equations (1) and (2) to estimate the fuel consumption and emission rates. The final models involved numerous polynomial equations that correlate speed and acceleration levels as input data and MOEs as output data. These models fit EEAA data accurately at medium speed ranges and various acceleration levels. The coefficient of determinationfor the MOEswas estimated using Equations (1) and (2). The results indicated a good fitfor nitrogen oxides(R2=0.95), average fit forfuel consumption, carbon dioxide and hydrocarbon estimates (R2=0.90), and a relatively poor fit for carbon monoxide emission (R2=0.70).

TABLE 1. Regression coefficients for diesel fuel

Fuel Consumption Coefficients FC				
Dependent Variable: lnFC				
	Constant	Speed	Speed²	Speed³
Constant	0.479	0.076	-0.003	
Acceleration	0.282	0.049	-0.003	
Acceleration²	-0.039			
Acceleration³	-0.042			
Carbon Dioxide Coefficients CO_2				
Dependent Variable: lnCO_2				
	Constant	Speed	Speed²	Speed³
Constant	-0.405	0.038		
Acceleration	0.25	-0.023		
Acceleration²	0.12	-0.061	0.003	
Acceleration³				0.001319
Carbon Monoxide Coefficients CO				
Dependent Variable: CO				
	Constant	Speed	Speed²	Speed³

Constant	2.414	0.052		
Acceleration	0.661			
Acceleration^2	-0.242		0.001	
Acceleration^3	-0.144			

TABLE 1. (Cont.) Hydrocarbon Coefficients HC

	Dependent Variable: lnHC			
	Constant	Speed	Speed^2	Speed^3
Constant	2.206	0.061		
Acceleration	0.075	-0.007		
Acceleration^2		-0.002		
Acceleration^3				

Nitrogen Oxides Coefficients NO_x

	Dependent Variable: NO_x			
	Constant	Speed	Speed^2	Speed^3
Constant	0.0000001	5.094	-0.448	0.011
Acceleration	1.187			
Acceleration^2				
Acceleration^3				

TABLE 2. Regression coefficients for gasoline fuel

Fuel Consumption Coefficients FC

	Dependent Variable: lnFC			
	Constant	Speed	Speed^2	Speed^3
Constant	-0.214			
Acceleration	0.507	0.018		
Acceleration^2				
Acceleration^3	-0.064			

Carbon Dioxide Coefficients CO_2

	Dependent Variable: CO_2			
	Constant	Speed	Speed^2	Speed^3
Constant	1.103	0.155	-0.007	
Acceleration	0.768		-0.002	
Acceleration^2	0.148	-0.025		
Acceleration^3	-0.077			

Carbon Monoxide Coefficients CO

	Dependent Variable: CO			
	Constant	Speed	Speed^2	Speed^3
Constant	72.014			

Acceleration	-8.375	2.413		
Acceleration²		0.503		
Acceleration³				

TABLE 2. (Cont.) Hydrocarbon Coefficients HC

	Dependent Variable: lnHC			
	Constant	Speed	Speed²	Speed³
Constant	2.404			
Acceleration		0.039		
Acceleration²				
Acceleration³				

Nitrogen Oxides Coefficients NO_x

Dependent Variable: $lnNO_x$				
	Constant	Speed	Speed²	Speed³
Constant	0.993	0.085		
Acceleration		0.036		
Acceleration²				
Acceleration³				

TABLE 3. Regression coefficients for natural gas fuel

Fuel Consumption Coefficients FC

Dependent Variable: lnFC				
	Constant	Speed	Speed²	Speed³
Constant	2.149	-0.077		
Acceleration	0.363			
Acceleration²	-0.276	0.077	-0.004	
Acceleration³				0.00002683

Carbon Dioxide Coefficients CO_2

	Dependent Variable: CO_2			
	Constant	Speed	Speed²	Speed³
Constant		1.374	-0.15	0.004
Acceleration	1.266		-0.004	
Acceleration²				
Acceleration³	-0.178			

TABLE 3. (Cont.) Hydrocarbon Coefficients HC

	Dependent Variable: lnHC			
	Constant	Speed	Speed²	Speed³
Constant	2.445	0.282	-0.031	0.001
Acceleration	-0.198		0.001	

Acceleration²				
Acceleration³				-0.0000148

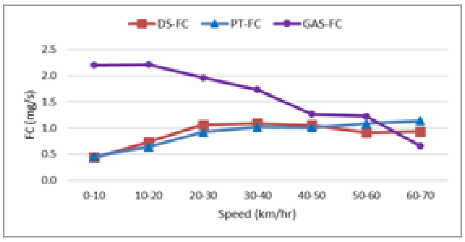
Nitrogen Oxides Coefficients NO_x

Dependent Variable: NO_x				
	Constant	Speed	Speed²	Speed³
Constant	33.914			
Acceleration	12.192			
Acceleration²		0.411		
Acceleration³	-3.865	0.44		-0.002

For better understanding for the various relationshipsamong the MOEs, illustrations between tailpipe emission and fuel consumption were plotted against a mixing of speed values and acceleration levels for more deep assessment.The first attempt to describe the impact of traffic and vehicle characteristics on fuel consumption and emissions was to describe the impact of different levels of speed on the MOEs. The objective of this analysis was to provide recommendations and references for the future improvement projects regarding design speed and running speed values. To conduct this analysis, the test vehicles travelled at speed ranging from 10.0 up to 60 km/hr.We suggested this speed limit because it is the most widely travelling speed in Greater Cairo Region. Second-by-second fuel consumption and emissions records were used and integrated over the entire trips to compute the fuel consumption and emissions values. The different relations between MOEs and corresponding speed level were plotted over a fixed section of 10.0 km/hr speed.

Figures3a, 3b, 3c, 2d and 3edemonstrated the nonlinear relationship between speed and fuel consumption valuesand emissions rates. In general, as the value of speed increased, the fuel consumption rate increased. The illustrationsdemonstrated that differences between the lowest and the highest fuel consumption values were approximately in a range of 300%. When a vehicle stop is introduced and as the travelling speed increases, the vehicle fuel consumption and emission rates increase.As illustrated in Fig.3, the emission rates exhibited more likely as a concave function with respect to speed. The variation in CO2 and HC emission rate constituted a difference in the range of 300% over speed ranges from 0.0 km/hr to 60 km/hr. Regarding CO performance, the minimum CO emission rate was achieved fromnatural gas fuel with almost constant trend, while diesel fuel exhibited a variation in the range of 1000% andgasolineexhibited a variation in the range of 200%. The variation in NOx emission rate is similar for gasoline and diesel with a difference in the range of 200% over the 0.0 to 60.0 km/hr speed range,whileNOx emission rate for natural gas was almost constant.It is demonstrated well from Fig.3 that there is no constant relationship between speed and tailpipe emissions. Similar observation is noted by other researchers such as Frey et al. [14] and Oses et al. [15].

Also,the literature review guidedus to study the effect of acceleration and deceleration to describe the impact of congestion on fuel consumption and emissions.To do that, authors segregated the impact of speed on emission rates and fuel consumption and the impact of the different acceleration and deceleration level.The acceleration and deceleration were computed as the first derivative of the instantaneous on-board speed measurements. Sometimes, due to some mistakes in the speed records, the acceleration estimates resulted in unrealistic values exceeded the expected maximum acceleration that a vehicle can achieve.These unrealistic values were segregated and omitted. The distribution of computed acceleration and deceleration for the entire trips is illustrated in Figs. 4a, 4b, 4c, 4d and 4e.As shown in Fig.4, the acceleration levels that were experienced by the majority of the travelling vehicles fall between 0.0 m/s2and3.0m/s2, while the decelerations levels fall between 0.0 m/s2 and -2.0 m/s2. Tailpipe fuel consumption and emission rates; CO, CO2, HC and NOx were plotted against the average acceleration and deceleration levels. As illustrated in Fig.4, the fuel consumption values exhibited a convex function with respect to the acceleration and deceleration values. The fuel consumption started to decreasefrom its values at the deceleration of -2.0 m/s2, reaching its minimum value at a deceleration of approximately 0.00 m/s2and then started to increasewhiletheacceleration increase. For emission rates, it can be observed from this figure that emission rates increase with the increasingof vehicle acceleration levels. This implies that the lower acceleration the lower tailpipe emission rates and the higher acceleration the higher emission rates. However, tailpipe emission rates in deceleration mode are very low when compared with emission rates in acceleration mode. Possible reason to understand this performance is that the deceleration is achieved by application of vehicle brakes and separation of the engine. During the deceleration, the engine is detached from the vehicle and hence it doesn't contribute in the process of deceleration.The difference in the performance of the case of the deceleration and acceleration could be attributed to the fact that in the deceleration the vehicle does not exert power, while in the acceleration the vehicle exerts power.



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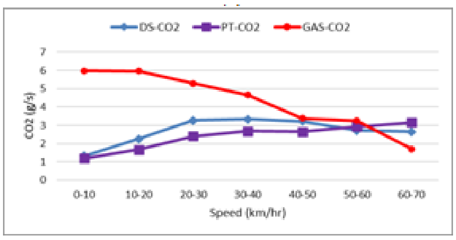

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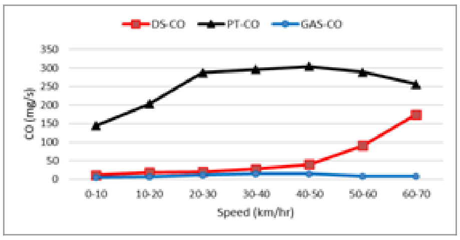

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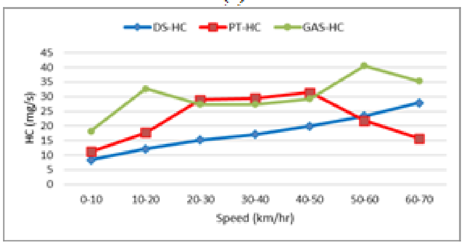

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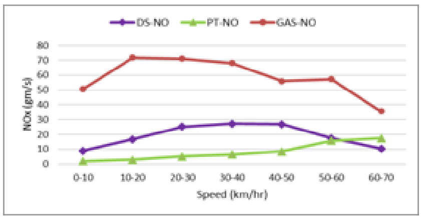

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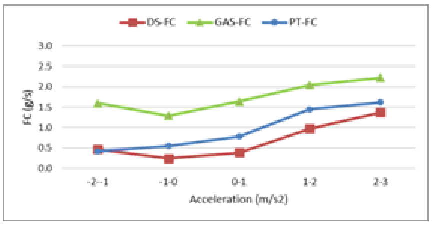
FIGURE 3. Relation between speed and MOEs



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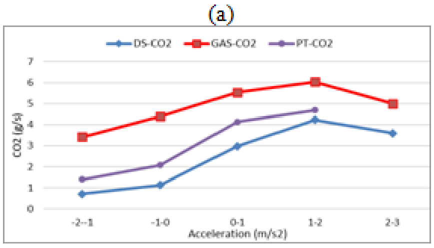

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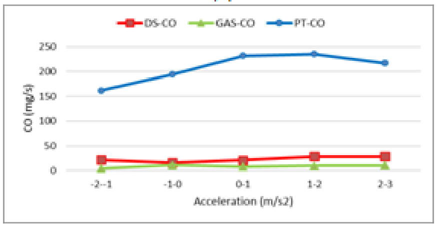

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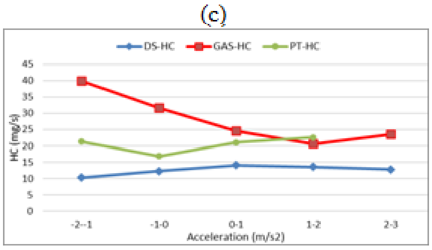

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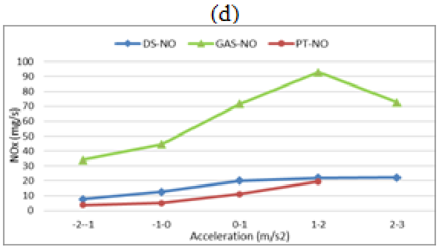

(e)

FIGURE 4. Relation between acceleration and MOEs

5. CONCLUSION

Emission and fuel consumption models were developed for natural gas, gasolineand dieselfuels using SPSS software and on-board measurements of speed and tailpipe emissions data. The final polynomial regression functions usedinstantaneous speed and acceleration as independent variables.The study demonstrated that the fuel consumption and emissions are highly correlated with acceleration andspeed.The authors realize that continuous enhancements to the predicted fuel and emission models are required. From the study, authors summarized the followings results:

- The developed regression modelsfor fuel consumption and emissions included a combination of linear, quadratic, and cubic terms for speed and acceleration with a relatively good fit to EEAA data.
- These models can be used to compute the fuel consumption and emission rates using on-board instantaneous speed and emission data.
- The available on-board measurements and the models can be used to comparethefuel consumption and emission rates with respect to the different fuel types.
- For speeds in the range of 10 km/h to 70 km/h, while the speed is increasing, the power is reducing and hence the fuel consumption rate is reducing.
- The majorrecommendation for this study is that vehicles should be driven at approximately constant speed, as much as possible, to consumelower fuel and consequently lower emission.
- Noteworthy is that the acceleration levelshave a great impact on the emissionmore than the impact of the increasing speed.
- Furthermore, it can be observed that the effect of acceleration on tailpipe emissions is more prominent at medium speeds.The analysis indicated that the fuel consumption and emission rates were insensitive to the level of deceleration.
- The authors realize that continuous improvement for the developed models can be achieved by studying more test vehicles and collecting more measurements.

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