Impact of Acceleration Aggressiveness on Fuel Consumption Using Comprehensive Power Based Fuel Consumption Model

Peter Bakhit[1], Dalia Said[2*], Laila Radwan[3]

1. M.Sc. Candidate, Public Works Department, Faculty of Engineering, Cairo University, Giza, 12316, Egypt
2. Assistant Professor, Highway and Traffic Engineering, Public Works Department, Faculty of Engineering, Cairo University, Giza, 12316, Egypt
3. Professor, Highway, Traffic, and Airport Engineering, Public Works Department, Faculty of Engineering, Cairo University, Giza, 12316, Egypt

* E-mail of the corresponding author: daliasaid@eng.cu.edu.eg

Abstract

Changes in vehicle fuel-consumption and emission rates are associated with changes in vehicle cruise speeds and acceleration. Higher levels of speed is believed to be one of the most prevalent factors contributing to fuel consumption. As a result, the relationship between fuel consumption and driving speed behaviour has been the subject of investigation by several research. The main objective of this paper is to investigate the fuel consumption during different acceleration degrees namely: aggressive, normal and mild. The test vehicle was examined on a 2 km section of Cairo - El Ain El Sokhna Road. The three levels of acceleration were determined based on pre-developed drive scenarios. In addition, fuel consumption was estimated based on a Virginia Tech Power Based Fuel Consumption Model (VT-CPFM). This model is a simple and rapid method for investigating fuel consumption rates. The study demonstrated that the fuel consumed to accelerate an initially stationary vehicle was not related to the target speed as to driving behaviour. It was also observed that the fuel consumed per maneuvers decreased as the degree of aggressiveness increased due to the fact that the vehicle time spent during acceleration was less.

Keywords: Fuel consumption, VT-CPFM, Acceleration levels.

1. Introduction

Vehicular emissions and energy consumption are two significant measures of effectiveness (MOE) of sustainable transportation processes. Transportation accounts for 20% of the total energy consumption and air pollution. In recent years, there has been considerable attention on fuel-economic driving behaviour. Many booklets offering drivers fuel-saving tips have been published. These booklets typically offer advice on fuel-efficient accelerations. Although advice to the general public on fuel-efficient accelerations is widespread, there appears to be little experimental information on this subject in the technical literature. In the 1960's. Scheffler and Niepoth (1965), had drivers complete the General Motor (GM) city-suburban test schedule on a test track using double (and half) the acceleration and deceleration rates originally specified for this schedule. This change led to a 7% increase (decrease) in the amount of fuel required to complete the schedule. In the 1990's, Watson & Laker (1980), used a computer simulation of a small British car to calculate the amount of fuel used to accelerate at various rates from rest to 60 km/h and travel a fixed total distance. It was found that an average acceleration of about 0.7 m/s^2 resulted in minimum fuel consumption. Jones (1982) tested a 1979 compact car on a dynamometer and measured the amount of fuel used to reach a constant speed of 89 km/h (and travel a fixed total distance) for five different average accelerations ranging from 0.45 m/s^2 to 2.2 m/s^2. It was found that, within this range of accelerations, fuel consumption monotonically decreased with decreasing acceleration rates.

Everall et al. (1985) and Chang and Herman (1979) experimentally investigated how fuel use in traffic depended on such driver goals as "drive to save fuel" or "drive to save time". The results of such experiments were interpreted to suggest that the driver behaviour changes that led to decreased travel time (e.g., increased levels of acceleration) would generally increase fuel use in approximately the same proportion. As a result, quantifying the impact of acceleration levels on fuel consumption even by minor proportions might lead to considerable pay-offs with regards to saved fuel. Accordingly, the experimental study described in this study was undertaken to generate more comprehensive information on how the amounts of fuel used to reach a target speed were affected by different acceleration levels. Moreover, the proposed evaluation approach presented a rapid and easy to use strategy for estimating fuel consumption during any acceleration event.

Automobile fuel consumption varies according to the conditions under which the automobile is being operated. Variations in vehicle emissions and fuel consumption rates are connected with changes in vehicle cruise speeds and acceleration. There are several methods to measure fuel consumption including more accurate, conventional methods or less accurate, and less expensive methods. The conventional chassis dynamometer test is an example of an accurate, but costly method where tests are performed at a well prepared equipped facility. However, a less expensive, and straight forward process can be easily performed to measure fuel consumption using simulation mechanistic models validated against in-field data. For instance, in a research at Virginia Tech Transportation Institute (VTTI), the research workers carried out a field investigation of fuel economy and emissions rates of one motor test vehicle during different cruise speeds and acceleration rates (Rakha et al, 2011). They could only cover speeds somewhere between 40 mph and 60 mph and this was mainly due to the fact that the testing was carried out on public roads. The final results from this research provided the ability for transportation planners to examine the energy effects of different acceleration degree levels.

This paper is organized in 5 sections. Section 1 briefly overviews introduction and background studies in this area. Section 2 describes the proposed model structure and framework. It also includes the mathematical relations on which the model is base on. Section 3 presents the research methodology and the experimental work followed in the study. Section 4 investigates the impact of the different acceleration levels on fuel consumption. Finally, the study conclusions are presented in Section 5.

2. Modeling Framework

Research in fuel consumption has been undertaken since the first motor vehicle was invented. Initially, scientists (e.g.de Weille, 1966) used course empirical data in building the fuel consumption empirical models. Recently mechanistic models were developed from the relations connecting engine efficiency and the forces opposing motion (Greenwood and Bennett, 1995a). Greenwood and Bennett (1995a) stated that “mechanistic models are considered to be markedly superior to empirical models in that they directly account for the individual vehicle characteristics and the forces acting on the vehicle”. As a result, a microscopic mechanistic model named Virginia Tech Comprehensive Power based Fuel consumption Model (VT-CPFM) were considered for the research study in hand. The disadvantage of current state of art models were their use of bang-bang control and the difficulty in calibration of the model parameters (Rakha et al, 2011). This takes place simply because the partial derivative of the fuel consumption rate with respect to the engine motor torque (*T*) is not a function of torque (Saerens et al., 2010). A model that produces a bang-bang control system problem would certainly point out that the excellent fuel economy control would eventually be to speed up at full throttle. The VT-CPFM-1 proposed by Rakha et al. (2011) provided data on fuel consumption without bang-bang control and made use of publically accessible Environmental Protection Agency (EPA) city and highway data. This model was validated against in-field fuel consumption rates with a reliability of approximately 92% during model testing and validation.

The Virginia Tech Comprehensive Power-based Fuel consumption Model was used to investigate the fuel consumed with different acceleration levels. The developer used four major criteria in model construction: real-time computation, accuracy, model structure, and model calibration simplicity. Rakha et al. (2011) proposed two models to satisfy the previous criteria. One used fewer inputs without the knowledge of specific vehicle information but came at the cost of some accuracy. The second model needed more information about the specific vehicle that was being used, but provided more accuracy as demonstrated by experimentation. In order to keep the focus of this paper on a more general scale of fuel and acceleration relationship, the first model (VT-CPFM-1) will provide the basis of fuel consumption calculation. Both models are very similar in terms of mathematical equations and calculations. The basis of determining vehicle fuel consumption model is described in the following equation:

$$FC = \begin{cases} \alpha_{\circ} + \alpha_1 P(t) + \alpha_2 P(t)^2 & P(t) \geq 0 \\ \alpha_{\circ} & P(t) < 0 \end{cases} \quad (1)$$

Where: $\alpha_{\circ}$, α_1 and α_2 : are vehicle-specific model constants

$P(t)$: Instantaneous power at time (t)

The model states that the fuel consumption (*FC*) is related to the power (*P*) that the car is producing. The (α) variables are representative of general vehicle parameters. If power at time (*t*) is less than zero, then fuel consumption at time (*t*) is equal to α_0 (representative of fuel consumption while idling), otherwise the fuel consumption is a product of vehicle characteristics, roadway conditions, and power at time t. *P(t)* can be calculated based on the following equation,

$$P(t) = \left(\frac{R(t)+1.04\,ma(t)}{3600\eta_d}.v(t)\right) \quad (2)$$

Where m corresponds to vehicle mass (kg), $a\ (t)$ is the acceleration of the vehicle at time t (m/s^2), η_d is the driveline efficiency or the efficiency with which the vehicle transfers its power from the motor to the tires (%), and v(t) is the speed at time t (m/s). *R (t)* is a resistance function determined by drag, rolling resistance (friction), and grade resistance and is defined as:

$$R(t) = \frac{\rho}{25.92} C_D C_h A_f v(t)^2 + 9.80066m\frac{C_r}{1000}(C_1 v(t) + C_2) + 9.8066mG(t) \quad (3)$$

In this equation, ρ is the density of air at sea level at a temperature of 15 °C (59 °F) (equal to 1.2256 kg/m3), C_D is the vehicle drag coefficient, C_h is the correction factor for altitude (equal to 1-0.085H, where H is the altitude in kilometers), A_f is the frontal area of the vehicle (m^2), C_r, C_1, and C_2 are coefficients associated with rolling, and *G(t)* is the grade at time *t*. For this model, the altitude will be 48 meters assumed sea level (H=0 km, C_h= 1.0) and the grade will be assumed level causing the last term to drop.

After the instantaneous power is determined, the alpha variables associated with vehicle parameters are found. The first alpha variable, α_0, is defined by the model as,

$$\alpha_o = \frac{P_{mfo}\omega_{idle}d}{22164 \times QN} \quad (4)$$

In this instance P_{mfo} is the idling fuel mean pressure (400,000 Pa) (Rakha et al, 2011), ω_{idle} is the idling engine speed (rpm), d is the engine displacement (liters), N is the number of cylinders, and Q is the fuel lower heating value. After the determination of α_0 the other alpha variables can be estimated according to the following equations from the model,

$$F_{city} = T_{city}\alpha_o + P_{city}\alpha_1 + P^2_{city}\alpha_2 \quad (5)$$

$$F_{hwy} = T_{city}\alpha_o + P_{hwy}\alpha_1 + P^2_{hwy}\alpha_2 \quad (6)$$

T_{city} and T_{hwy} are the time of the highway and city drive cycles provided by the Environmental Protection Agency, EPA (1874 s and 763 sec respectively), whereas P_{city}, P_{hwy}, P^2_{city} and P^2_{hwy} are the summation of power and power squared over these city and highway cycles (Environmental Protection Agency, 2010). To prevent the bang-bang control and ensure convexity in the fuel consumption-power relationship, bounds are introduced for all alpha variables as defined in (Rahka et al. 2001). For convenience, the parameters used in this study are outlined in Table 1 along with their source.

Table 1 shows the input parameters for the 2014 Kia Cerato test vehicle used in this study. The data includes parameters for the estimation of the various resistance forces. Some model parameters may be assumed as will be described. The engine efficiency accounts for the power losses in the engine due to internal friction and other factors. This factor ranges between 5-15% for light- and heavy duty vehicles. The frontal area of the vehicle can be approximated to 85% of the vehicle height multiplied by its width if it is not given directly in the vehicle specifications. The air drag coefficient is typically provided on auto manufacturer websites, however if this parameter is not available typical values for light-duty vehicles range from 0.30 to 0.35, depending on the aerodynamic features of the vehicle. Heavy-duty vehicles have much higher drag coefficients ranging from 0.58 to 0.78. The tire size for the test vehicle is reported as P195/60 R15 on the KIA motors website. The 195 parameter is the tire width in millimeters, measured from the bottom of the bead to the bottom of the bead, the 60 is the sidewall aspect ratio, the ratio of sidewall height to tire width at the tread (indicating that the sidewall height is 60% of the tread width), and the 15 is the wheel rim diameter in inches.

Table 1. Model Parameters

Parameter	Recommended for VT-CPFM 1	Value	Reference (Source)
Model year	Yes		Auto Website
wheel Radius	No		Auto Website
idling speed	No	600 -750 rpm	Auto Website
Redline speed	No		Auto Website
Downshift Speed	No	1500 rpm	Field data
Upshift speed	No	3400 rpm	Field data
vehicle Mass (kg)	Yes		Auto Website
Drag Coefficient(C_d)	Yes		Auto Website
Frontal Area (A_f)	Yes	0.85*Height*Width	Auto Website
Rolling Coefficient (C_r)	Yes	1.75	(Rakha et al,2001)
C_1	Yes	0.0328	(Rakha et al,2001)
C_2	Yes	4.575	(Rakha et al,2001)
Driveline Efficiency	Yes	85-95 %	(Rakha et al,2001)
Wheel slippage	Yes	2-5 %	(Wong, 2001)
Number of Cylinders	Yes		Auto Website
Engine size (L)	Yes		Auto Website
Number of Gears	No		Auto Website
Various Gear Ratio	No		Auto Website
Final Drive Ratio	No		Auto Website
P_{mfo} (Pascal)	Yes	400000	(Wong, 2001)
Q(J/kg)	Yes	43000000	(Wong, 2001)

METHODOLOGY

The methodology followed in this study consisted of two main sets. First, extracting speed profiles from field experiments. Secondly, inserting speed profiles into the computer model to analyze the effect of acceleration levels on fuel consumption. The experimental design of the on-road data collection involved selecting the test vehicles, the test site, driving patterns, and developing the test protocol. This section provides a brief description on these elements.

3.1 Test Vehicle Specification

A KIA- Cerato of model 2014 (K3) was selected for modeling and experimental purposes. The motor vehicle was powered by a 1.6 liter (1600 CC), V-4 engine using an 92 -octane fuel, rated at 130 hp @ 6300 rpm, with an electronic six-speed automatic overdrive transmission. The vehicle had a mileage of 4000 km at the start of the tests. Figure 1 shows the test vehicle and GPS used in the experiment. The vehicle could be easily modified to set up different equipment in order to track the vehicle speed profile.

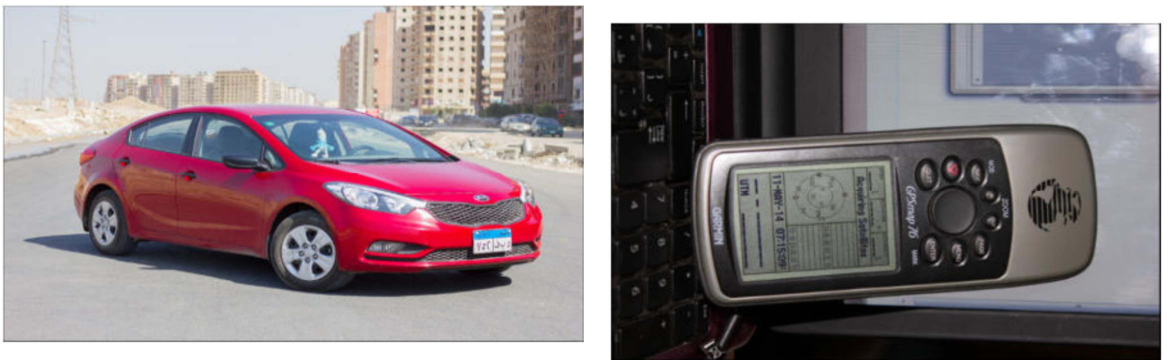

Figure 1. Test Car and GPS used in the Experiment

3.2 Data Collection Equipment

The GPS receivers were essential to track record the vehicle's exact path and speed during the experiment. A GPSMAP 76 was used as a handheld GPS device as shown in Figure (1). The GPS device was differential-ready that read coordinates from 20 satellites to work with high efficiency. The GPS accuracy was from 3-5 meter and speed accuracy was about 0.1 Knot RMS steady state. The GPS was connected directly to the laptop inside the test vehicle and the data transfer second by second. For the objective of this experiment, the GPS receiver was set to record coordinates and speed at an interval of one reading per second.

A 2 km test section on Cairo- El Ain El Sokhna Road was selected to execute the experiment, as shown in Figure 2. The road was designed with high geometric standards. Traffic volumes are low on the road, enabling collection of fuel consumption data with minor traffic interruptions.

In order to isolate the impact of various degrees of acceleration aggressiveness on fuel-consumption, different acceleration levels (mild, normal and aggressive) were tested. Each test or run involved accelerating an initially stationary vehicle to a target speed of 100 km/h. The vehicle was first positioned at a marked starting point and idled at standstill for at least 25 seconds. After this preparatory period, the data-collection devices were enabled and the driver accelerated the vehicle to the target speed stated above. The acceleration degrees were defined as the time needed to reach the 100 km/h target speed. The aggressive acceleration attained 100 km/h in approximately 20 seconds which represented 50% of the maximum acceleration envelope. While normal and mild acceleration degrees reached the target speed in 58 and 78 seconds respectively. Speeds were recorded with a one-second time interval using the GPS. The test procedure was repeated ten times for three levels of acceleration over a 2 km section of Cairo- El Ain El Sokhna Road. One of the challenges was to reach a speed of 100 km/h at the same time span for 10 consecutive runs.

Figure 2. Test-Site Description

Table 2 shows the time spent to reach the target speed and the percentage of each acceleration degree from the maximum acceleration envelope. Finally, ten speed profiles were created for each acceleration level resulting in 30 speed profiles

Table 2. Acceleration Degree Description

Acceleration Level	Time Taken to Reach 100 km/h (secs)	% of Maximum Acceleration Envelope
Mild	78 sec	15%
Normal	58 sec	20%
Aggressive	20 sec	50%

4. Impact of Different Acceleration Levels on Fuel Consumption

The analysis presented within this study systematically quantified the real impact of different vehicle acceleration degrees on vehicle fuel-consumption. Data was collected in 30 individual tests, involving one target speed, 3 levels of acceleration, 10 runs for each level. The acceleration levels were produced by the driver based on vehicle maximum acceleration envelope. According to the test vehicle manual, the vehicle can reach a target speed of 100 km/h in 10.1 second. The principal objective of these experiments was to extract speed profiles representing the different acceleration degrees. For the three acceleration levels, the second-by-second speed change measurements illustrate that the test motor vehicle reached a target speed of 100 km/h in 20s for the maximum-acceleration scenario, as illustrated in Figure 3. It should be mentioned that the vehicle travelled along a straight segment with mild uphill and downhill slopes that varied between 0.5 and 1.5%.

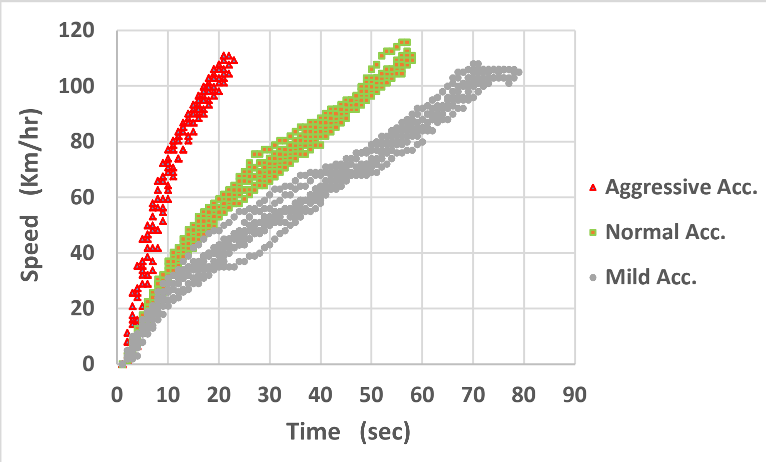

Figure 3. Instantaneous Second by Second Speed Profiles of Different Acceleration Levels

As shown in Figure 4, the aggressive acceleration test reflects the steepest slope among the acceleration tests, as would be expected. In addition, the experiment illustrated that the instrumented vehicle throughout the aggressive acceleration runs reached the target speed of 100 km/h before the vehicle travelled a distance less than 0.4 km. The normal acceleration test demonstrated that the test vehicle attained the 100 km/h target speed in approximately 0.9 km, while the vehicle during mild acceleration reached a 100 km/h target speed in a distance of approximately 1.1 km.

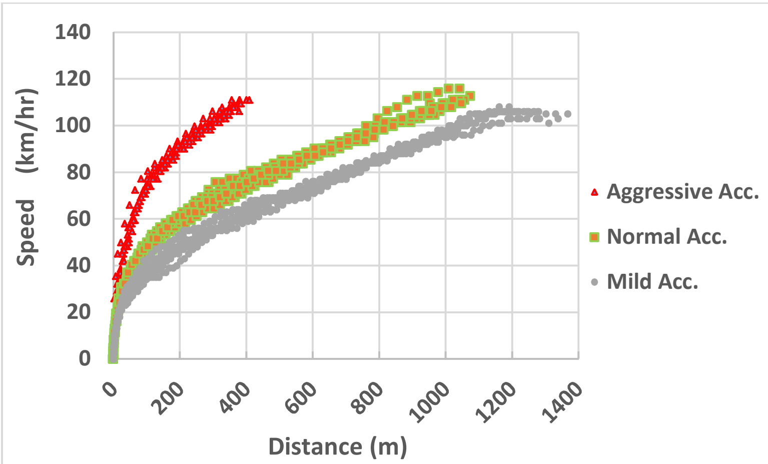

Figure 4. Instantaneous Second by Second Speed Profiles of Different Acceleration Levels with Respect to Distance

The speed profiles for the different types of accelerations, mild, normal and aggressive were entered into CPFMs to estimate cumulative and instantaneous fuel-consumption for each cycle during each run, as shown in Figures 5, 6 and 7. The data obtained for each acceleration type was analyzed in a similar manner. To illustrate this procedure, the aggressive acceleration analysis will be presented in details.

The aggressive acceleration level was considered one of the most popular driving behaviour in driving modes. Therefore studying this type of acceleration precisely might represent or introduce new outcomes helpful in advising future drivers. Figure 7 demonstrates clearly the aggressive way of driving through instantaneous speed changes. For example, moving from 20 km/h to 40 km/h took less than 2 seconds, while in normal driving cycle it took around 8 seconds. This aggressive trend continued till reaching the target speed of 100 km/h in 20 seconds. The aggressive behaviour was also observed in the instant acceleration profile. Due to the increased rate of change of instantaneous speeds, the acceleration rates raised significantly. It started hitting a peak of 5 m/s^2 before the steady drops to a bottom low of 1 m/s^2. After that, the acceleration rates continue fluctuating until reaching the end of the profile. The average acceleration rate for the whole aggressive cycle was around 1.45 m/s^2 compared to 0.55 m/s^2 and 0.39 m/s^2 in normal and mild acceleration respectively. With respect to the instantaneous fuel consumption rates, Figure 7 shows the performance of the test vehicle under aggressive driving behaviour. Fuel consumption rates raised significantly compared to those of mild and normal acceleration levels. The fuel consumption rates rise steadily in the first 4 seconds, then there was a sudden increase to a value of 8 ml/s. From second 6 to second 17, there were fluctuations ranging between 2 ml/s to 10 ml/s. The line ends the cycle in 20 seconds at approximately 6 ml/s.

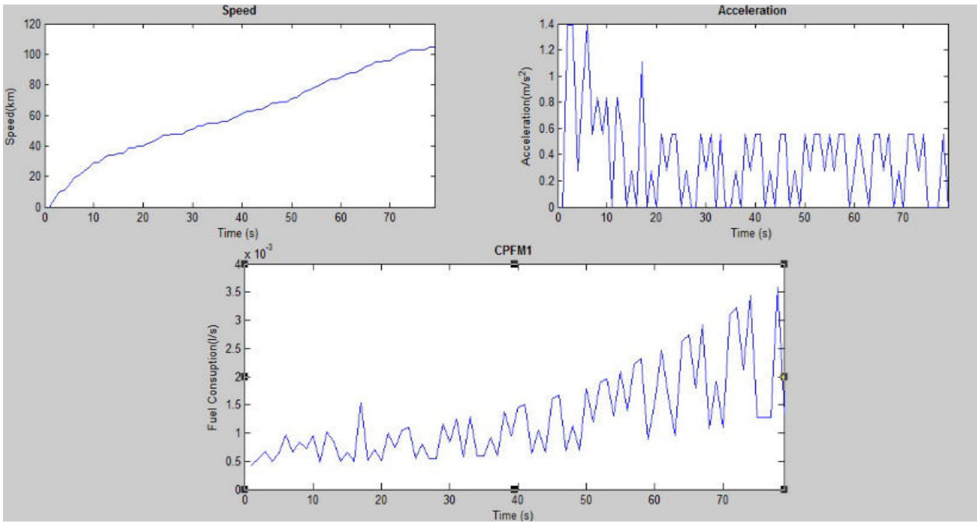

Figure 5. Mild Acceleration Analysis

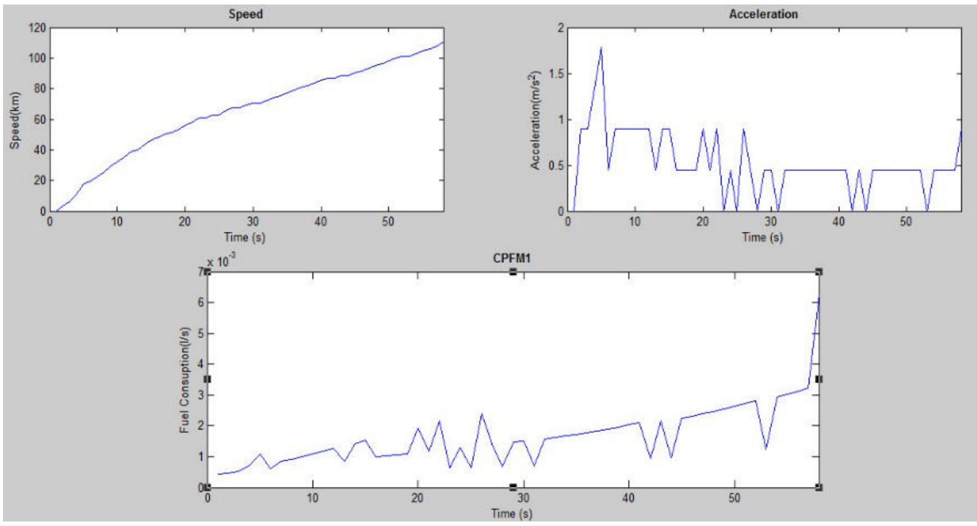

Figure 6. Normal Acceleration Analysis

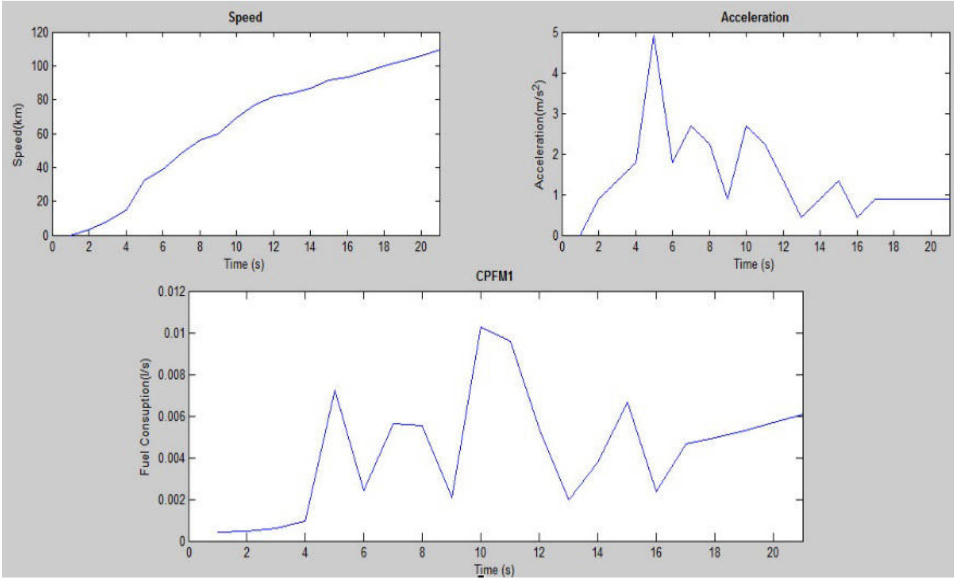

Figure 7. Aggressive Acceleration Behaviour

It should be noted that the model measurements are averaged over the ten test runs and the fuel consumption was computed for each of the ten speed profiles and averaged over the ten runs. The aggregate fuel measurements for each acceleration type maneuver is illustrated in Figure 8.

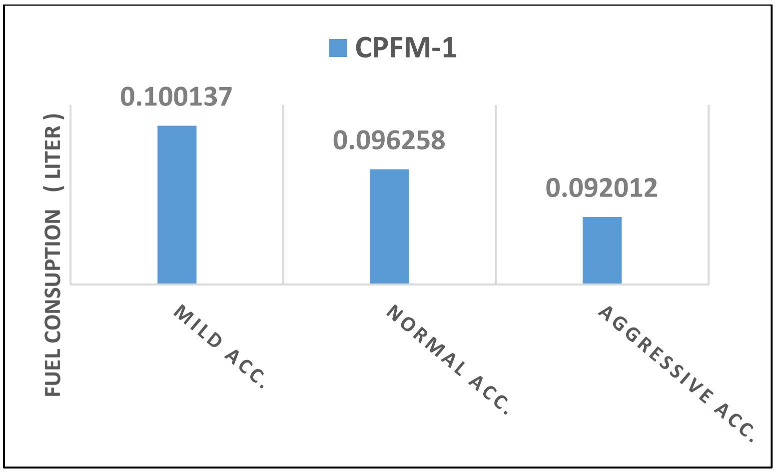

Figure 8. Fuel Consumed during Mild, Normal and Aggressive acceleration levels

In this paper the driver is defined as the operator of a motor vehicle and the difference between driving patterns of the vehicle and driver is known as aggressiveness. A number of general conclusions can be drawn from this study. For example, the fuel consumed to accelerate an initially stationary vehicle is not related to the target speed as to driving behaviour. Moreover, the rate of fuel consumed (lit/s) increased as the speed increased. Accordingly, the major factor affecting the fuel consumption is the time spent in acceleration process. As a result, the analysis demonstrated that the fuel consumption per maneuvers decreased as the degree of aggressiveness increased due to the fact that the vehicle time spent during accelerating was less.

5. Conclusions

The goal of this study was to investigate driver and vehicle aggressiveness on fuel consumption. Based on the results it can be seen that as the aggressiveness increased, the fuel consumption per maneuver decreased, due to the less time spent in acceleration. Secondly it has been noted that the MATLAB® VT-CPFMs showed to be easily calibrated using publically accessible data with no need to gather field instantaneous data. This model also provided a simple method to investigate fuel consumption under different driving behaviour in different events. Finally, fuel consumptions and levels of accelerations experiment that was mentioned earlier demonstrated that, the fuel consumption varied directly with the different degrees of accelerations. It can be noticed that the fuel consumed in case of aggressive acceleration was less than that of mild acceleration by 8 %. While the normal acceleration consumed about 3.8% more than mild acceleration.

References

Chang, M. F., and R. Herman, (1979) "Driver Response to Different Driving Instructions Effect on Speed, Acceleration and Fuel Consumption," *General Motors Research Laboratories*, September 1979.

Chang, M. F., L. Evans, R. Herman and P. Wasielewski, (1977) "Gasoline Consumption in Urban Traffic", *Transportation Research Record*, Washington, D.C., No.599.

Greenwood, I.D. and Bennett, C.R. (1995a). "HDM-4 Fuel Consumption Modelling. Preliminary Draft Report - Task 2020-3," *International Study of Highway Development and Management Tools*, University of Birmingham.

Jones, R. (1980) "Quantitative Effects of Acceleration Rate on Fuel Consumption", *US Environmental Protection Agency*.

Rakha, H. A., K. Ahn, K. Moran, B. Saerens, and E. V. d. Bulck, (2011) "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model Development and Testing," *Transportation Research Part D: Transport and Environment*, vol. 16, pp. 492-503.

Rakha, H., I. Lucic, S. H. Demarchi, J. R. Setti, and M. Van Aerde, (2001) "Vehicle dynamics model for predicting maximum truck acceleration levels," *Journal of Transportation Engineering*, vol. 127, pp. 418-425.

Scheffler, C. E. and G. W. Niepoth, (1965), "Customer Fuel Economy Estimated from Engineering Tests." *Society of Automotive Engineers*, SAE Paper 650861. November 1965.

U.S. Environmental Protection Agency, (November 2010), "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2010." *Technical Repor*t EPA-420-R-10-023. http://www.epa.gov/ otaq/cert/mpg/fetrends/420r10023.pdf; pp. 5-34.

Watson, M.H., and I. B. Baker, (1980) "Research on Fuel Conservation for Cars*", Transport and Road Research Laboratory*, England.

Wong, J. Y. (2001), *Theory of Ground Vehicles*, John Wiley & Sons, Inc.