

# Estimation of the effect of the driving style on pollutants emission by heavy trucks

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*Abstract:* - Emissions derived from the use of internal combustion engines for transportation, are being the subject of many efforts to minimize them. In this respect, despite its potential importance in reducing fuel consumption and emissions, driving style still has not been priced. In this paper, a hybrid GPS data – simulation methodology is used to identify the travel kinematic characteristic that most strongly influence fuel consumption and corresponding pollutants emissions. Existing formulations are used to estimate the fuel consumed during five trips along a highway, performed by different drivers and monitored through a GPS device. The methodology represents a model to be used for road tankers, which involve special driving restrictions and sloshing effects. Results indicate that the longitudinal acceleration's standard deviation keeps an almost linear relationship with the fuel consumed, so that such kinematics can provide an objective metric to assess eco-driving. It is suggested to include non-exhaust pollutants into the analysis, which have been reported as having dangerous effects on humans.

*Key-Words:* - Driving style, fuel consumption, stored energy, GPS data, simulation, particle emissions

## 1 Introduction

The World Health Organization has reported that transport partly contributes to 2 million premature deaths each year due to urban outdoor air pollution [1]. Additionally, pollution is contributing to a climate change characterized by stronger hurricanes and extreme weather, with the corresponding quota of mortality and morbidity rates [2]. By the year 2000, it was reported that suspended particles, to which heavy truck's diesel engines are important contributors, represented in the Europe Community approximately 8.5 months of lost life per person, while in 2002, 3.3% of deaths of adults older than 30 years in France were linked to fine particles [3]. However, the mounting transportation demand and the multidisciplinary nature of any potential change, confronts any effort to reduce fuel consumption and pollutants emissions. While all kind of vehicles are of interest in diminishing pollutants emissions, freight transport is of particular interest, as such

transportation sector emits close to one-third of U.S. transportation greenhouse gases; has grown up 50% since 1990; and it is anticipated to double in the U.S. by 2035, and to triple internationally [4].

Consequently, the implementation of policies aimed at getting overall reductions in fuel consumption and emissions is challenging, as improvements in fuel efficiency of transports are offset by increments in the transportation demand. For example, in the EU-27 countries, an increase on energy efficiency of 15% between 1990 and 2008 has been reported, which was clearly offset by an increase of 27% in the demanded energy [5]. That is, a drastic enhancement in fuel utilization, greater than such percentage, would only satisfy an effective fuel consumption reduction.

Reported improvements in fuel and vehicles efficiency have included systematic approaches to cope with this issue. For example, the pollutants that the vehicles emit into the environment have been classified as [4]: criteria pollutants (carbon

monoxide, nitrogen dioxides, ozone, particulate matter, sulfur dioxide and lead); mobile-source air toxics (acrolein; benzene; 1,3-butadiene); and Greenhouse gases (carbon dioxide). Moreover, a family of technological strategies to reduce fossil-fuels-derived emissions is now identified, as follows [4]: exhaust after-treatments (remove pollutants from the exhaust stream); repowering (replace older engines with cleaner burning equipment); alternative fuels (cleaner burning fuels); and energy efficiency (save fuel/emissions through superior design; e.g. hybrid-electric vehicles).

Concerning the operational side of the vehicles and its relationship with the environment, driving techniques for saving fuel/reduce emissions have been focused on promoting smooth accelerations/decelerations [4], together with what has been called green logistics, aiming at minimizing fuel consumption through rational routing [4] [5] [6] [7]. Particularly, enhancement of driving techniques has become a promising measure to reduce fuel consumption and, in 2006, some countries in Europe agreed a 10-year goal for training vehicle operators to achieve a 10% fuel saving thorough a better driving style [8]. Nevertheless, while some policy practices have been implemented for environmental pricing as a function of the day of the week, road type and vehicle characteristics [9], driving style has not been directly priced, in spite of its importance for the environment and that, on the other hand, also affects infrastructure condition [10].

In this paper, global positioning data are used to simulate vehicle's fuel consumption as a function of road characteristics and driving style, further discussing a performance measure for pricing driving style.

## 2 Acceleration values and fuel consumption

Combination of GPS data and emissions models have been considered in the past, with some variants according to the type of modeling or formulation. However, none of the proposed systems has considered an analysis based upon real second-by-second GPS data, used together with validated formulations for pollutants emission. Venter and Joubert [11] proposed a GPS-data fuel consumption estimation as a function of the time and day in an urban network, as a function of average speeds and distance travelled. Wang et al. [12] carried out a study to estimate fuel consumption and resultant pollutants emission as a function of acceleration under two traffic scenarios, on the basis of

acceleration measurements made through stationary sensors. They consider both, average acceleration of vehicles in the traffic, and the standard deviation of such variable, reporting an important sensitivity for the variation in fuel consumption with variations in the average acceleration (41 liters per  $m/s^2$  of average acceleration). That is, decreasing average acceleration from 0.023 to 0.022  $m/s^2$  represented decrements in fuel consumption from 9.0266 to 8.98 liters per 100 km (-0.46 %), and a reduction in NOx emitted from 7.37 to 7.34 grams per vehicle (-0.286%). Sensitivity of fuel consumption to acceleration's standard deviation resulted in 0.41 liters per  $m/s^2$  of acceleration's standard deviation. Based on regression analysis, Kim and Choi [13] describe a study in which increments in fuel consumption and CO<sub>2</sub> emission increase exponentially with acceleration and define a critical value for the acceleration from the environmental perspective, around 1.4 and 2.27  $m/s^2$ . They calculate standard deviations of the acceleration, but do not integrate them as an assessment tool. Haobing et al. [14] employ GPS data together with the program MOVES to estimate emissions, on the basis of a long ten-second interval data, which is interpolated in order to have second-by-second data. The unit time fuel consumption variation for a vehicle is estimated through a simplified formulation proposed by Akçelik and Besley, as follows [15]:

i) For  $R_T > 0$

$$\Delta F = \left\{ \alpha + \beta_1 R_T v + \left[ \left( \beta_2 M_v a^2 v / 1000 \right)_{a>0} \right] \right\} \Delta t \quad (1)$$

ii) for  $R_T \leq 0$

$$\Delta F = \alpha \Delta t \quad (2)$$

where:

$R_T$  Total tractive force (kN) required to drive the vehicle, which is the sum of rolling resistance, air drag force, cornering resistance, inertia force and grade force;

$M_v$  Vehicle mass (kg) including occupants and any other load (10000 kg);

$v$  Instantaneous speed (m/s);

$a$  Instantaneous acceleration rate ( $m/s^2$ ), negative for deceleration;

$\alpha$  Constant idle fuel rate (mL/s), as an estimate to maintain engine operation (0.71);

$\beta_1$  Efficiency parameter which relates fuel consumed to the energy supplied by the engine (mL/kJ)(800 for heavy trucks), and

$\beta_2$  The efficiency parameter that relates fuel consumed during positive acceleration, to the product of inertia energy times acceleration (mL/(kJ m / s<sup>2</sup>)) (200 for heavy trucks).

During positive acceleration, the total tractive force is related to the inertial force ( $F_a = M_v a$ ). During zero acceleration, however, the only tractive force needed is the one necessary to overcome the drag and rolling resistance forces, together with the gravity force associated to a positive grade. During deceleration, a minimum fuel consumption is considered ( $\alpha$ ). The rolling resistance force is calculated through the following equation, which is based on empirical parameters [16]:

$$F_{rr} = C_r (c_2 V_{kph} + c_3)(W)(0.001) \quad (3)$$

where  $V_{kph}$  is the vehicle speed (km/h);  $W$  is the instantaneous vehicle load (N);  $C_r$  is the rolling coefficient (2.25 for smooth asphalt pavement); and  $c_2$  y  $c_3$  are rolling constants, as a function of the type of tire (0.0328 and 4.575, respectively, for radial tires)[16]. Calculation of the drag force, is based upon the following basic aerodynamics equation [17]:

$$F_d = C_D A_p \frac{\rho}{2} V^2 \quad (4)$$

where  $C_D$  is the drag coefficient,  $A_p$  is the vehicle's projected front area (11 m<sup>2</sup> in this case); and  $V$  and  $\rho$  are the air's speed and density, respectively. The longitudinal component of the vehicle's weight,  $F_w$ , is given by:

$$F_w = W \sin \lambda \quad (5)$$

where  $\lambda$  is the instantaneous road grade. Substitution of equations (3) to (5) into equation (1), yields that the increment in fuel consumption is given by:

$$\Delta F = \left( \alpha + \beta_1 \left[ \begin{array}{l} C_r (c_2 V_{kph} + c_3)(W)(0.001) + C_D A_p \frac{\rho}{2} V^2 \\ + W \sin \lambda \end{array} \right] v \right) \Delta t + \left[ (\beta_2 M_v a^2 v / 1000)_{a>0} \right] \quad (6)$$

For this research, the instantaneous acceleration and the road's slope are obtained from GPS data, acquired at a sample rate of 1 Hz, which is the maximum frequency for commercial GPS devices, but small enough to calculate accelerations under a non-emergency driving circumstance.

### 3 Road tankers perspective

Due to regulations or to operational conditions, drivers of certain heavy trucks must adapt their driving style in view of the cargo's nature. Such is the case of a transport carrying liquid cargo at partial fill levels, whose motion within the containers affects the lateral stability of the vehicle and its driving performance [18]. Figure 1 illustrates a sloshing cargo during a braking maneuver. The recommended driving style in this case, has to do

with imposing speed limits, while avoiding harsh accelerations or decelerations maneuvers [19].

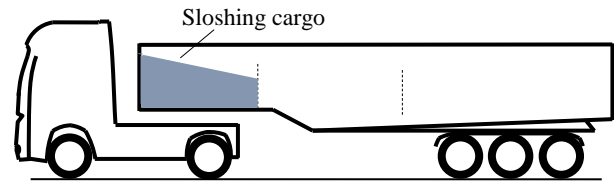


Fig. 1 Sloshing cargo condition in a road tanker carrying out a braking maneuver.

In the case of liquid cargo transportation, the driving style strongly influences the corresponding environmental externalities, according to the following phenomena:

- i) The sloshing cargo can generate vibrations in the vehicle that can generate driver fatigue, with potential catastrophic consequences when incidents occur, involving boiling liquid expanding vapor explosion (BLEVE) [20]. The sloshing energy can be directly affected by the driving style imposed, that influence the magnitude of the sloshing.
- ii) The vapors generated by volatile organic compounds (VOC), are influenced by the level of agitation within the containers, which depends on the driving pattern imposed on the vehicle by the driver [21]. Such VOC could be emitted into the atmosphere and become non-exhaust emissions.

In the following section the above described methodology is used to assess the driving of a vehicle which has different characteristics from a road tanker truck. It thus represents an example of the use of the methodology, which can be used to assess situations involving other heavy trucks in general, and road tankers in particular.

### 4 Results

The models described by equation (6) are used to simulate the effect of acceleration variations on fuel consumption of a two-axle straight truck traveling along an 80 km-segment of a Mexican three-lane highway. Five trips along the same 80-km length road segment were examined to study the effect of driving accelerations on fuel consumption. Trips were characterized by the standard deviation of the acceleration ( $\sigma$ ), as follows: 0.17, 0.18, 0.26, 0.32 and 0.36 m/s<sup>2</sup>.

Figure 1 illustrates some inputs and outputs of the proposed model, for a 20 km-long road segment, in which a smooth drive was applied, resulting in a standard deviation of 0.17 m/s<sup>2</sup> for the acceleration

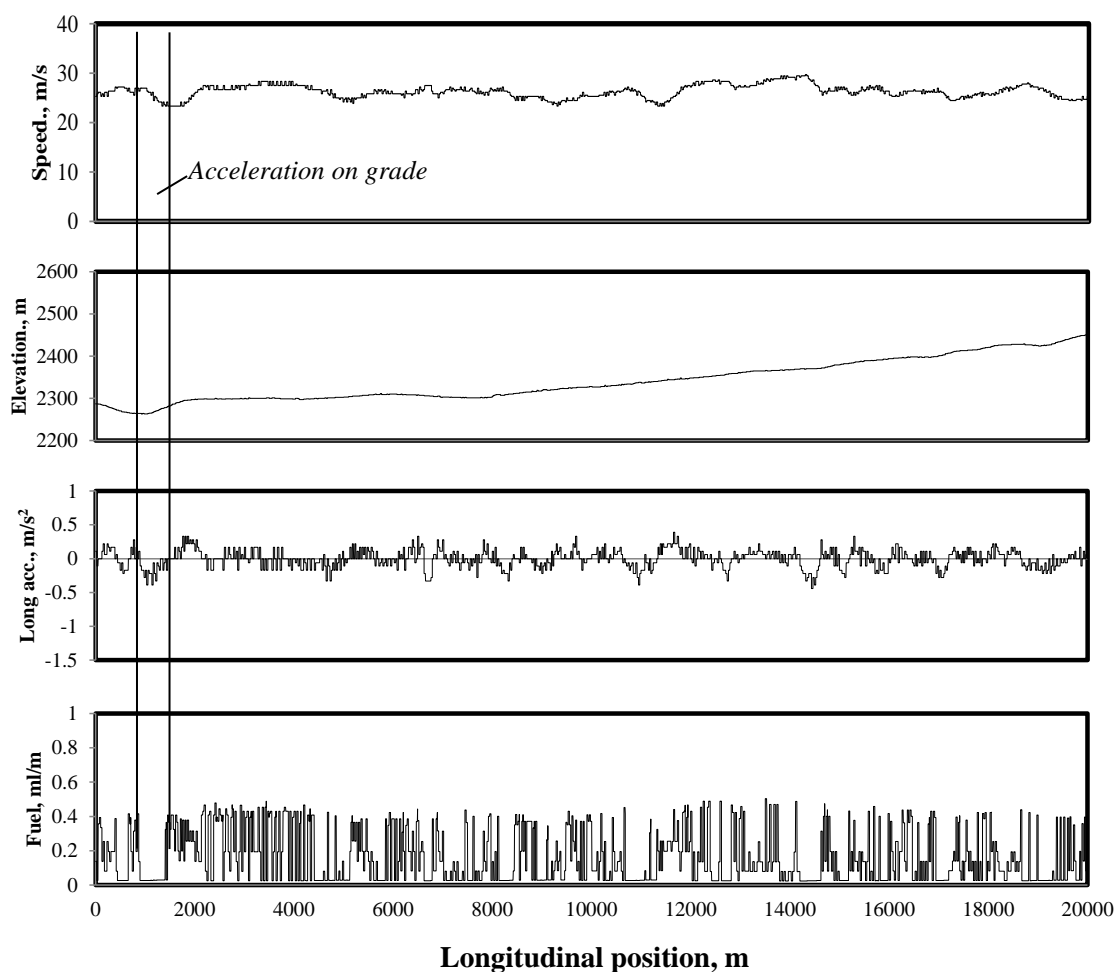


Fig 1: Sample of space variation of inputs and outputs to/from the fuel consumption model.

While speed and elevation are two of the inputs, the longitudinal acceleration and fuel consumption per unit length, are the main outputs of the model. Results in this case reveal strong variations of the outputs, as a function of the road elevation and of the acceleration inputs.

Figure 2 describes the spatial variations of the five acceleration outputs for the corresponding trips considered in this study, where each of these trips had a different standard deviation. These acceleration profiles represent different driver's attitude at driving, where a maximum acceleration is detected around  $2 \text{ m/s}^2$  in the case of part (d) and part (e) in this figure, while a maximum deceleration was observed in the case of part (e), with a value of  $3.5 \text{ m/s}^2$ . It should be noted that these acceleration profiles were obtained under no traffic congestion condition, so that the speed changes where the direct result of driver style for performing passing maneuvers and for managing of the space between vehicles.

Figure 3 illustrates global results of the effect of both the longitudinal acceleration dispersion and the vehicle average speed, on the fuel consumption rates. These results suggest an almost linear relationship between the acceleration dispersion and the fuel consumption, with a strong sensitivity of 21.5 liters per each  $\text{m/s}^2$  of standard deviation. This figure also includes the  $\text{NO}_x$  emissions, assuming an average of 3985 gr of  $\text{NO}_x$  per liter of fuel [12]. In case that the non-exhaust emissions were considered in the analysis, the positive accelerations would be related with the tire wearing, while the braking dust emissions would be related to the braking manoeuvres carried out during the traveling. However, high traction forces  $R_T$  would also be present in case of high speed or grades, according to Eq. (1) above. Fuel consumption of a common truck has been thus estimated based upon existing and well-known methodologies. Results reveal a strong effect of acceleration dispersion on vehicle's fuel consumption, which results much greater than the one reported in the literature.

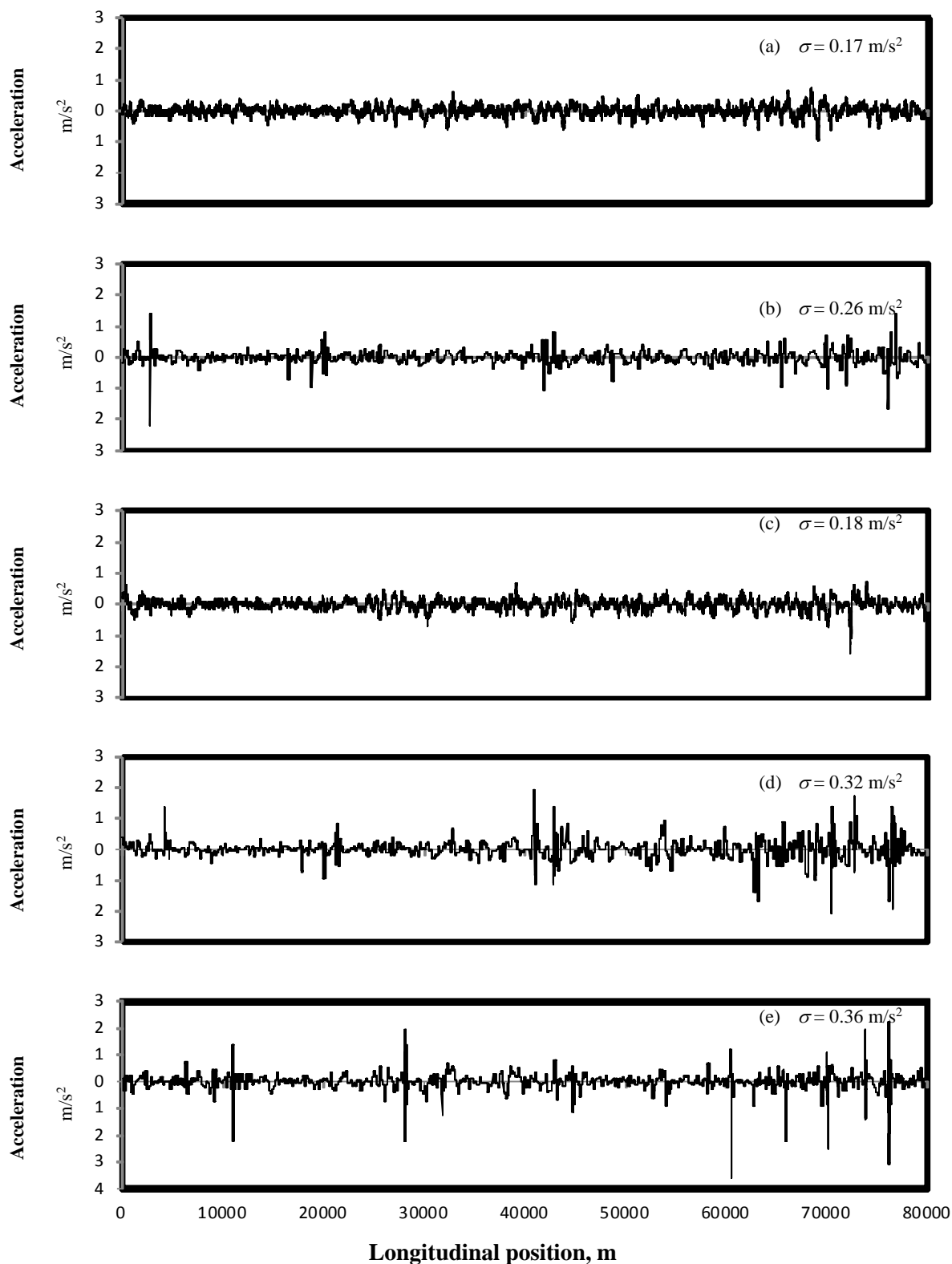


Fig 2: Longitudinal acceleration profiles for the five trips considered for analysis, in terms of that acceleration standard deviation  $\sigma$ .

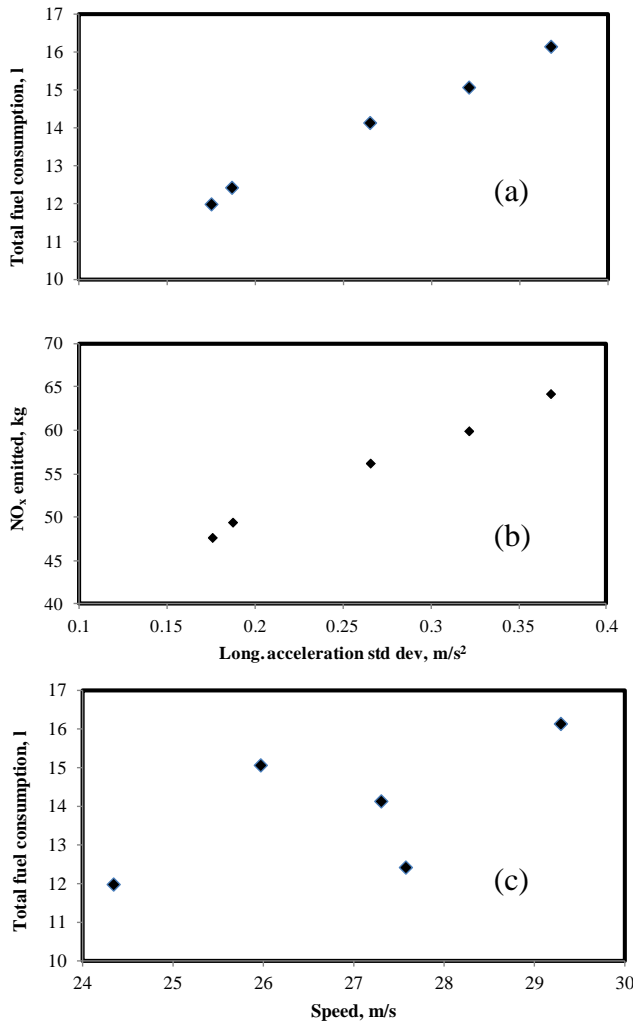


Fig. 3 Effect of kinematic characteristics on total fuel consumption.

That is, while in [12], this sensitivity of the fuel consumption to the acceleration's standard deviation, is 0.41 liters per m/s<sup>2</sup> of acceleration's standard deviation, the corresponding value from the simulations carried out in the present paper, is 21. Such a big difference is attributed to the different driving regimes considered in the respective situations, and to the method of acquiring the data. While in [12] the source of information derived from a stationary vehicle; in this paper, realistic GPS data were considered.

On the other hand, the average speed outputs in this figure 3, suggest that this variable does not correlate with the total fuel consumption. In this respect, the relationship of this output and the standard deviation of the longitudinal acceleration, is presented in Figure 4, where it can be noticed that a harsher driving does not correlate in general with a faster driving. Nevertheless, the lowest and highest conditions do correlate. That is, the faster driving involved also the harsher driving, while the slowest one involved the smoother one.

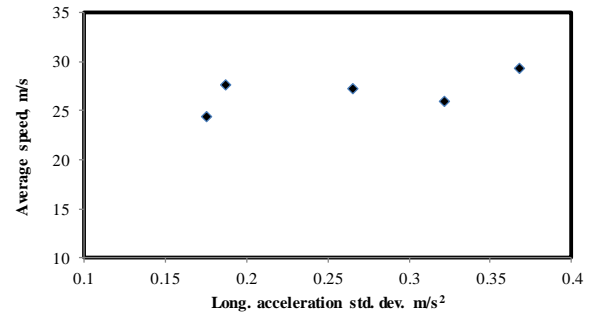


Fig. 4 Relationship between two input variables .

However, a performance measure based upon the acceleration standard deviation could be a first step towards generating a mixed index under which both speed and acceleration were taking into account. A composite index could be thus defined under a scheme similar to existing approaches in transportation systems, such as the one designed to characterize road roughness (International Roughness Index), which is calculated on the basis of a measured road profile and the simulation of the dynamic response of a simplified vehicle, to such pavement profile [22].

On the other hand, in the last years attention has been paid to other negative effects, directly related with the acceleration level imposed to the vehicle, which is the non-exhaust related emissions (Particulate matter, PM), related to the brake and tire wear [23].

## 5 Conclusions

Different approaches have been attempted so far to reduce fuel consumption and linked pollutants, including vehicle equipment and design, with rational driving style being recognized as a potential source of fuel savings. However, no specific methodology had been suggested so far to assess fuel economy of driving other than the fuel consumed itself. In this paper, the standard deviation of driving acceleration has been found to be directly associated to fuel consumption, so that the less dispersion of the driving acceleration, produces the lower fuel consumptions and emissions. Such metric could be thus used to assess driving style.

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