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STUDY AND SIMULATION OF THE FUEL CONSUMPTION OF A VEHICLE WITH RESPECT TO AMBIENT TEMPERATURE AND WEATHER CONDITIONS

Mbelle Bisong Samuel [*1, 2, 3, 4], **Paune Felix** [5], **Youmene Nongosso Miguel** [1], **Tambere Samam A. cyrille** [1], **Pierre Kisito Talla** [2]

[1] ENSET Kumba, Cameroon
[2] LMMSP University of Dschang, Cameroon
[3] ENSET, University of Douala, Cameroon
[4] Ammosov's North-Eastern Federal University,58, Belinskogo, 677000, Yakutsk, Russia
[5] Génie Informatique et Automatique, UFD-SCI, ENSET, University of Douala, Cameroon

Abstract:

The consumption of fuel in vehicles depends on many factors such as the state of the roads, the state of the engine and the driver's behavior. A mathematical model for evaluating vehicle fuel consumption on a 100 km interval at standard operating weather conditions was developed. This mathematical model developed took into consideration many factors, but the main factors were those related to weather conditions and temperature. Here a new simulation program for determining the influence of temperature and weather conditions on fuel consumption is built using the software Matlab. For efficient simulations the model uses a set of data for an SUV and then makes varying only the parameters that are related to weather and temperature for the simulation. During the simulation process, a set of 10 vehicle models and 8 roads conditions were chosen to run down the simulations and only the parameters of temperature, the drag coefficient and coefficient of rolling resistances respectively were subjected to variations during each of the simulations. Upon simulation, different results were obtained for the different parameters considered. For every 15% drop in temperature, 0.1litre, 0.12litre and 0.04litre increase in fuel consumption for the set of parameters chosen was noticed. These results were analyzed and interpreted with the help of Microsoft Excel and were found to be satisfactory given that it permits manufacturers and car users to have a notion of the impact of ambient temperature and weather conditions on fuel consumption, thereby promoting optimum usage of fuel, hence reducing the effect of greenhouse emissions in the atmosphere.

Keywords: Fuel Consumption; Ambient Temperature; Weather Conditions.

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1. Introduction

In an automobile, fuel consumption is important to the users as well as the manufacturer. Given that the aim of every user is to obtain a minimal fuel consumption while maintaining the best performances of his vehicle, this article is going to raise awareness on the users on how fuel is being consumed and when best to use your vehicle ensuring optimum usage of fuel hence saving a lot of money and contributing to the reduction of environmental damages through air pollution caused by the fuel in the form of exhaust gases. In the literature, multiple dependencies of fuel consumption were constructed based on experimental data (approximation), but their purpose is largely confined to analyzing the influence of various factors on the fuel consumption of specific vehicles such as the power train, the driving style and many others. Most of them failed to consider natural factors such as weather conditions, whereas it has a great and significant influence on fuel consumption. The amount of fuel consumed depends on the engine, the type of fuel used, and the efficiency with which the output of the engine is transmitted to the wheels and many other parameters. This fuel's energy is used to overcome rolling resistance primarily due to flexing of the tires, aerodynamic drag as the vehicle motion is resisted by air, and inertia and hill-climbing forces that resist vehicle acceleration, as well as engine and drive line losses.

2. Materials and Methods

This section is concerned with the materials and the methods which were used in order to achieve a numerical relation between fuel consumption and ambient temperature, and also comprises the choice of the software which is going to be used in this project. Below is the list of the materials used for this project.

2.1. Materials

1) Matlab/Simulink
2) Microsoft excel 2016 version

2.2. Methods

2.2.1. Analytical Modeling Study

A study of the mathematical relations of the main factors that influence the fuel consumption of our vehicle and the manipulation of some equations to derive an equation that relates fuel consumption and temperature is done, taking into account the assumptions and the specifications of our model.
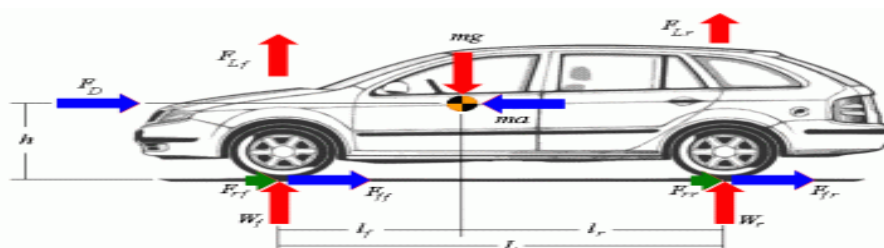

Figure 1: Image of a model vehicle showing the forces acting on it

The following assumptions were made as regard to this model for the simulation of fuel consumption of this model;

Table 1: Model vehicle parameters

Parameter	Value
vehicle speed	v=60km/h (16.67m/s)
acceleration due to gravity	g=9.81m/s^2
vehicle acceleration	a= 3m/s^2
mass of the vehicle	M= 1285kg
transmission efficiency	η_t=0.9
Rolling resistance coefficient	f_{rl}= 0.011
Aerodynamic drag coefficient	C_d= varies according to road profile
Diesel Fuel density	= 0.850kg/l
Frontal area of car, A_f	varies for each vehicle
Engine power at 6000rpm	P_e = 67kw
Pressure	P = 0.1bar = 0.1*10^{5}Pa

2.2.1.1. Aerodynamic Drag

Aerodynamic drag is the resisting force that air applies on a moving object like a ball, car, or aircraft. Basically, the object crashes into the air molecules in front of it. The air has to be pushed out of the way and the drag force comes from that air pushing back against the object. The drag force on an object, for instance a car, can be quantified using the formula:

$$F_D = \tfrac{1}{2}\rho v^2 C_D A$$

(1)

Where: FD is the drag force, ρ is the air density, v is the velocity, CD is a dimensionless drag coefficient, and A is the frontal area.

The magnitude of the density will decrease at higher humidity and/or elevation, but the trend as a function of temperature is essentially unchanged. Cold air is denser than warm air and the aerodynamic drag force is proportional to the air density.

2.2.2. Derivation of The Formula of Fuel Consumption with Respect to Ambient Temperature

In this paper, an estimation of fuel consumption QS measured inlitersper100km, with respect to the engine power via the following relation (Michael Ben Chaim, 2013);

$$Q_s = \frac{g_e(P_{rl}+P_w+P_a)}{10.V_a.\eta_T.\rho_f}$$

(2)

Assuming that the vehicle is constantly operating in acceleration mode and the engine power is determined according to this assumption. Specific fuel consumption is assumed to be constant and optimal.

Based on the equation of fuel consumption above, the calculations can be made providing the values for the following;

- Specific fuel consumption
- Power to overcome rolling resistance
- Power to overcome aerodynamic drag
- Power to overcome inertial acceleration
- The fuel density
- The efficiency of the transmission

The lower the brake specific fuel consumption, the more efficient the engine is. For **spark ignition** (gasoline engine) the BSFC is around **250 g/kWh** and for **compression ignition** (diesel) around **200 g/kWh**.(x-engineering.org, 2019)

2.2.2.1. Determination of Power to Overcome Rolling Resistance

According to Wong, 1993, 90-95% of the rolling resistance is caused by internal hysteresis, 2-10% by friction between the tire and the ground and1-3% is caused by air resistance. Below is the formula that can be used to calculate the rolling resistance of the wheels of a vehicle.

$$R_{rl} = f_{rl}W \tag{3}$$

Upon obtaining the rolling resistance force, the power required to overcome rolling resistance can be calculated as follows;

$$P_{Rrl} = f_{rl}WV \tag{4}$$

Where
f_{rl} is the rolling resistance coeficient,

$$f_{rl} = 0.01(1 + \frac{V}{147}) = 0.011 \tag{5}$$

2.2.2.2. Power to Overcome Aerodynamic Drag Force

Aerodynamic drag force is the resisting force that air applies on a moving object like a ball, car, or aircraft. Below is the formula used to calculate the aerodynamic drag of a vehicle;

$$R_a = \frac{\rho}{2}C_D A_f V^2 \tag{6}$$

In order to calculate the power, we have to make use of the relation;

$$P_{Ra} = R_a V \tag{7}$$

Where P_{Ra} the power to overcome aerodynamic drag is, R_a is the force due to aerodynamic drag and V is the velocity of the vehicle. Substituting R_a in the equation of P_{Ra}, we obtain the following;

$$P_{R_a} = \frac{\rho}{2} C_D A_f V^3$$

(8)

From the ideal gas equation, assuming dry air in our model, we can obtain the relation between temperature and density as (Charles' Law);

$$\rho = \frac{P}{R_d T}$$

(10)

Where P is the pressure of air, R_d is the gas constant (8.314J/molK), and T the ambient air temperature.

In the case of moist air, we have;

$$\rho = \frac{P}{R_d T_v}$$

(11)

Where T_v is the virtual temperature expressed as $T_v = T.(1+0.61r)$ with r being the water vapor mixing ratio.

Replacing (10) in (8) above leads to the following equation;

$$P_{Ra} = \frac{P.C_d.A_f.V^3}{2.R_d.T}$$

(12)

2.2.2.3. Determination of Fuel Density

An engine which uses diesel as its fuel is the case study. The density of diesel is given as ρ_f=**0.8325kg/l.** The measurements were made at 15.5°C and standard atmospheric pressure.

2.2.2.4. Determination of The Efficiency of Transmission

After measuring the power throughout the entire rpm range, transmission efficiency can be calculated using the relation;

$$\eta_t = \frac{P_a + P_{rl}}{P_e}$$

(13)

In order to obtain the relation between the fuel consumption and temperature, we replace equations (4), (8), (12) in equation (2).

$$Q_s = \frac{\frac{2\pi\eta_r \dot{m}_f}{\eta_c V_d p_{me} \omega_e}(f_{rl}.W.v + \frac{pC_d A_f v^2}{2R_d T} + M.a.v)}{10.v.\eta_t \rho_f}$$

(14)

The relation shows the dependence of temperature on the overall consumption of the vehicle. Replacing all the values of the respective parameters and the necessary assumptions made for this model leads us to a simpler relation of fuel consumption and temperature which can then be simulated.

2.2.3. Numerical Analysis of The Parameters of Fuel Consumption

2.2.3.1. Power to Overcome Rolling Resistance

$$P_{Rrl} = f_{rl}WV$$

= 0.011*1285*9.81*16.67
= 2,311.53W = 2.3kW

2.2.3.2. Power to Overcome Inertia Acceleration

$$P_a = M.a.v$$

= 1285*1*16.67
= 21,420.95 = 21.4kW

2.2.3.3. Power to Overcome Aerodynamic Drag Force

$$P_{Ra} = \frac{P.C_{d.}A_{f.}V^3}{2.R_{d.}T}$$
$$= \frac{10,000 * 0.29 * A_f * 16.67^3}{2 * 8.314 * T}$$
$$= \frac{807.9 * A_f}{T} kW$$

Replacing the numerical values of the powers and other parameters we obtain;

$$Q_s = \frac{g_e(P_{rl} + P_w + P_a)}{10.V_a.\eta_T.\rho_f}$$
$$Q_s = \frac{200(2.3 + \frac{807.9*A_f}{T} + 21.4)}{10 * 60 * 0.9 * 0.8325}$$
$$Q_s = \frac{200(23.7 + \frac{807.9*A_f}{T})}{499.6}$$
$$Q_s = \frac{200}{499.6}\left(23.7 + \frac{807.9 * A_f}{T}\right)$$

$$Q_s = 9.48 + \frac{323.41*A_f}{T}$$
(15)

After carrying out the simulation of the above equation, it can also be varied by varying the coefficients of drag for different vehicles so as to see how frontal area, together with aerodynamics affect the fuel consumption at different temperatures. For this, we obtain the following equation;

$$Q_s = 9.48 + \frac{1115.2 * C_d * A_f}{T} \qquad (16)$$

Considering weather conditions, different road conditions affect vehicle's fuel consumption differently, so in order to obtain the effect of rolling resistance on fuel consumption for different road conditions, for this simulation, the parameters of frontal area and drag coefficients were chosen for the Toyota Yaris 2014 model (A_f=2.14m², C_d=0.29), the following equation was obtained and was simulated;

$$P_{Rrl} = f_{rl}WV$$

$= f_{rl}*1285*9.81*16.67$
$= 210139.5 f_{rl}\text{W} = 210.1 f_{rl}\text{kW}$
Replacing the above in the equation of fuel consumption, we obtain;

$$Q_s = \frac{200(210.1 * f_{rl} + \frac{692.1}{T} + 21.4)}{10 * 60 * 0.9 * 0.8325}$$

$$Q_s = 84.1 * f_{rl} + \frac{277}{T} + 8.5 \qquad (17)$$

To validate the obtained formula, estimates of fuel consumption obtained by calculations via the formula were compared to experimental data available from manufacturers. The vehicle-specific parameters used were the engine type, automobile mass, maximum power and engine speed at maximum power.

Table 2: List of symbols

A_f	Frontal area	m²
A	Fuel consumption in neutral gear	l/100km
$\dot{m}_f$	Fuel efficiency rate	
R_d	Gas constant	J/Kg.K
Bm	Mass fuel rate	Kg/s
ρf	Fuel density	Kg/l
g	Acceleration due to gravity	m/s²
ge	Optimal specific fuel consumption	g/KW.h
frl	Rolling resistance coefficient	-
Mv	Vehicle mass	Kg
n_c	Number of cylinders	
n_r	Number of crankshaft rotation for a complete engine cycle	
η_c	The efficiencyof the gearbox	
η_d	Final drive	
ηt	The efficiency of the transmission	
Pa	Power required to overcome the resistance of the inertial acceleration	Kw
Pe	Engine power	Kw

Pa	Power required to overcome inertial acceleration	Kw
p_{me}	Mean effective pressure	Pa
Pmech	Mechanical power on the wheel	
P_{rl}	Power required to overcome the rolling resistance of the road	Kw
Pt	Total power required to overcome rolling resistance and air resistance by Vehicle	Kw
Pw	Power required to overcome the resistance of the air	Kw
Qs	Fuel consumption	g/KW.h
Ra or Cd	Aerodynamic drag of vehicle	
$R_{rl\,orfrl}$	The rolling resistance of the wheels of a vehicle	
V	Vehicle linear velocity	m/s
V_d	Cylinder displacement volume	m^3

3. Results and Discussions

The data for the following vehicles were run in the Matlab/Simulink software;

Table 3: Parameters of test vehicles

Data	Vehicle mark	Model	Coefficient of drag, C_d	Frontal Area, A_f(m2)
1	Alfa Romeo	145	0.32	2.08
2	Audi	A4	0.29	2.03
3	BMW	Compact	0.31	1.95
4	Chevrolet	Volt	0.28	2.16
5	Chrysler	Sebring	0.32	1.93
6	Citroen	Xantia	0.31	2.08
7	Fiat	Punto	0.30	1.95
8	Hyundai	Elantra	0.33	1.86
9	Mercedes Benz	E- Class	0.27	2.19
10	Toyota	Yaris	0.29	2.14

For temperature ranges of -15°C to 45°C we obtained the following results:

For the first simulation, the results obtained were due to the variations of frontal areas at different temperatures. Below is the graph obtained from the simulation with varying frontal areas.
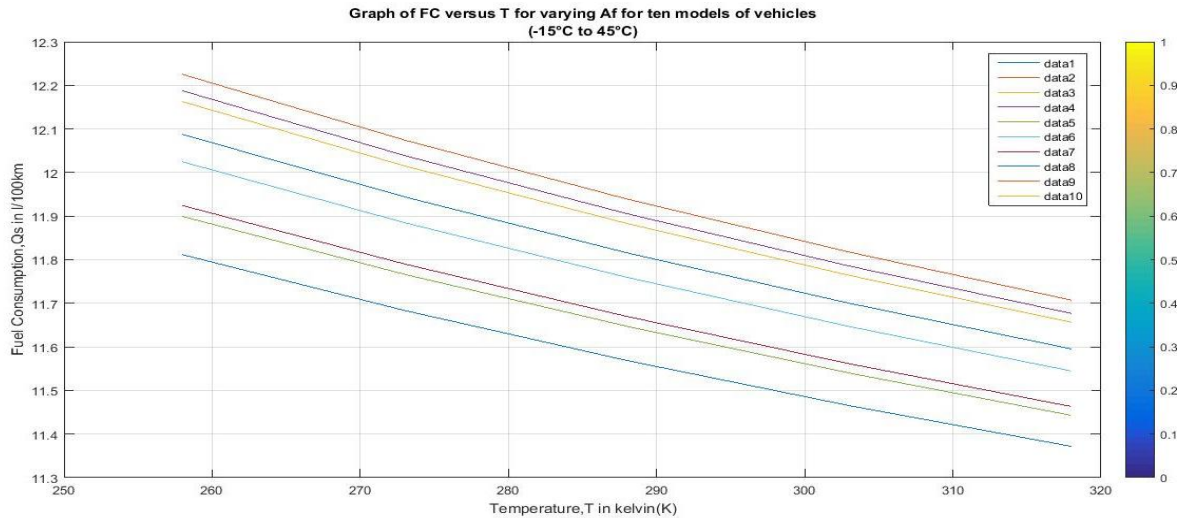
Figure 2: Graph of fuel consumption versus temperature (258k-318k)

The respective curves represent the different vehicles alongside their fuel consumption measured in litres/100km at respective temperatures during the driving cycle of 100km. The graph shows that the higher the temperature, the lower the fuel consumption for all the tests vehicles. It can also be observed that the vehicle frontal area affects the vehicle's fuel consumption linearly.

Another program was written to simulate the fuel consumption of the test vehicles with respect to temperature, while varying both the vehicle frontal area and the coefficient of aerodynamic drag force. Below is the result of its simulation;
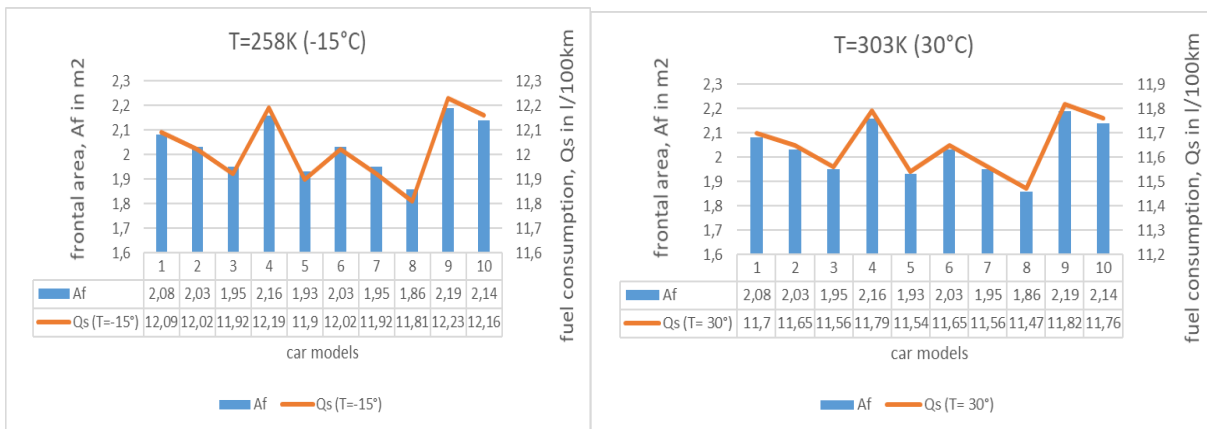

Figure 3: graph showing the effect of frontal Area on fuel consumption for a particular temperature of -15°C and 30°C for the test vehicles.

It can be observed from the above histograms, the value of fuel consumption obtained varies according to the temperature in a similar manner for all the test vehicles. Also it was noticed that for every 15°C drop in temperature, there is 0.1 litre increase in fuel consumption for the same vehicle and same frontal area and at the same speed. For the second simulation, the results obtained were due to the variations of both the frontal areas and coefficient of aerodynamic drag at different temperatures.

It can also be observed from this graph that the impact of higher drag coefficients and frontal area is of more significance, hence greater fuel consumption.
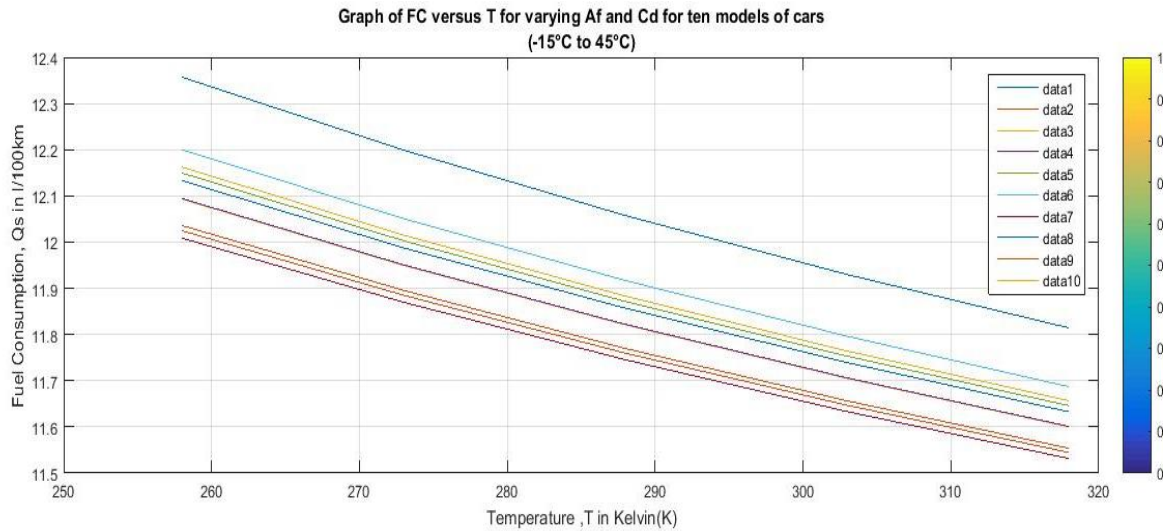

Figure 4: Graph of fuel consumption versus temperature (258k-318k)

The interpretation of this graph for each temperature range of 15°C using histograms was done. Below are the results for the temperatures of -15°C and 30°C.
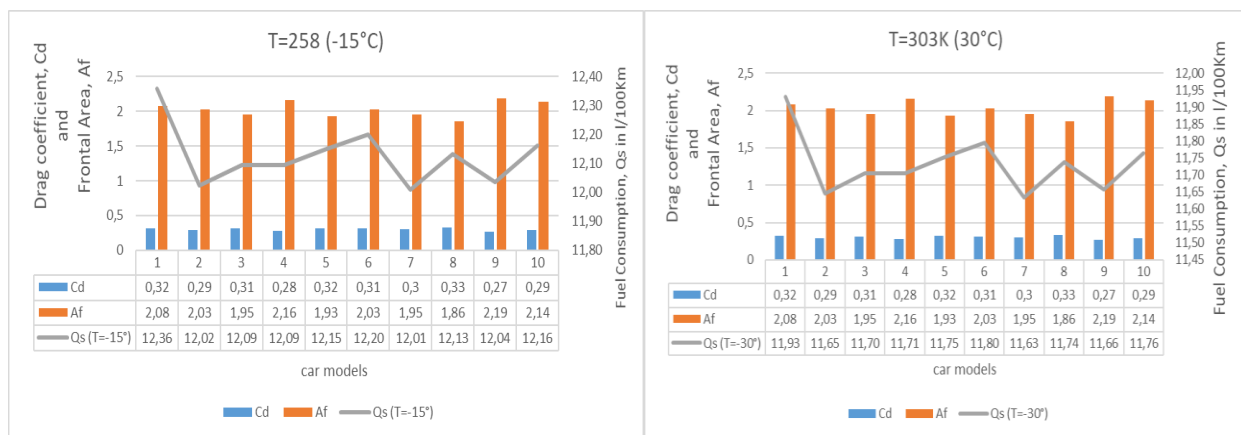

Figure 5: Graph of fuel consumption against drag coefficient and frontal area at a constant temperature of -15°C and 30°C for the ten test vehicles.

From the above histograms, one can notice that the value of fuel consumption obtained varies according to the temperature in a similar manner for all the test vehicles. Also, it was noticed that for every 15°C drop in temperature, there is 0.12litres increase in fuel consumption for the same vehicle and same frontal area, same drag coefficient and same speed.

For the third simulation, the results obtained were due to the variations of the rolling resistance coefficients at different temperatures. Below is the graph obtained from the simulation.
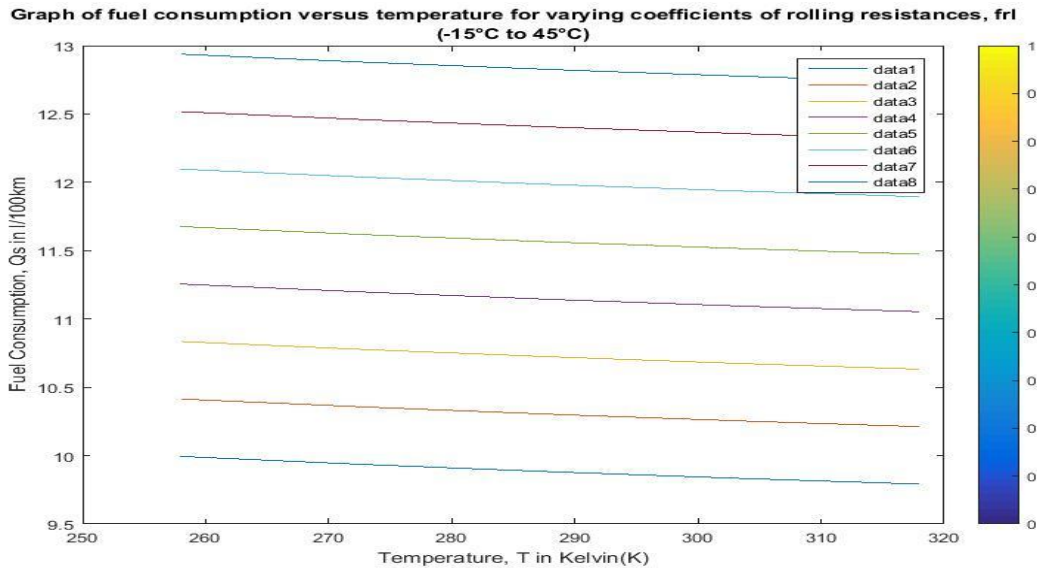
Figure 6: Graph of fuel consumption versus temperature (258k-318k)

The fuel consumption for the test vehicles was estimated for varying coefficients of rolling resistances at temperature ranges of -15°C to 45°C so as to explain the effects of different roads or different tires on the fuel consumption of the vehicle. The graph above shows the relationship between fuel consumption, coefficient of rolling resistance and temperature.

The interpretation of this graph for each temperature range of 15°C using histograms was done. Below are the results of the temperatures of -15°C, 30°C and 45°C
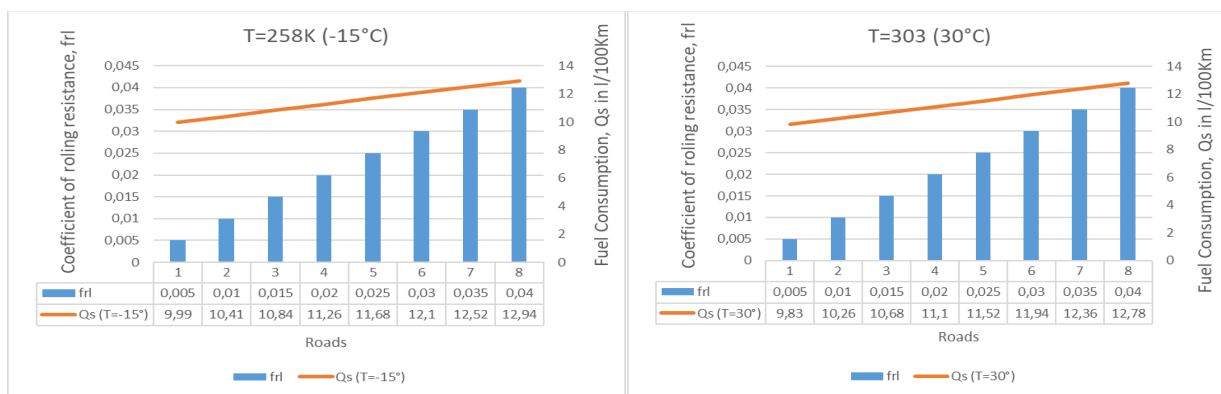

Figure 7: the graph of fuel consumption against rolling resistance for a constant temperature of -15°C for different road conditions.

The values of the coefficients of rolling resistance f_{rl} for each vehicle corresponds to the height of the rectangle of the said vehicle taken from the left of our graph, and the fuel consumed is the corresponding meeting point or extrapolation of the rectangle to the curve and then reading the value on the right hand side of our graphs to have the amount of fuel consumed by that vehicle. Also, it was noticed that for every 15°C drop in temperature, there is 0.04litre increase in fuel consumption for the same vehicle under the same road conditions and the same speed.

4. Conclusions

This paper presents a general view of how fuel consumption estimations are made. Based on a critical analysis of the main assumptions made in existing models in the literature, this work aimed at identifying the best compromise between accuracy and possibility to build up a straight forward and effective method, for the estimation of fuel consumption for vehicles whenever general operating data are publicly available.

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*Corresponding author.
E-mail address: mbellesabi@ yahoo.com /felix.paune@ gmail.com/ lokoromaric@ yahoo.fr/ tpierrekisito@ yahoo.com