Dependence of Fuel Economy on Speed for two Heavy Duty Vehicles

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ABSTRACT

Some recommendations have been made that vehicles should travel at certain speeds in order to reduce their fuel consumption because gasoline and diesel are currently very expensive in many countries. There is also the menace of fuel shortages approaching the near future in some parts of the world. These recommendations are based on the fact that on the road the fuel economy of a vehicle increases while travelling at cruise speed without acceleration, as it is shown in this paper. Some of the vehicles on the road are the heavy-duty vehicles which transport people, food, medicine, minerals, gasoline, diesel, and many other goods to keep the economy of any country running. The vast majority of heavy-duty vehicles on the road in the world still move with diesel engines. In this paper it is demonstrated, for the cases examined with heavy duty vehicles, that the fuel economy of vehicles depends on several factors which include the load transported, the acceleration to reach cruise speed, the engine, the gearbox, the wheels, the final drive, the maximum driving speed of the vehicles and the slope of the roads. The reduction of fossil fuels consumption in road transportation also reduces the emision of carbon dioxide to the atmosphere, a greenhouse gas which contributes to global climate change. For some of the cases studied the carbon dioxide emissions are also calculated. Savings in fuel consumption in dollars by driving at the best constant speeds and the reduction in the environmental cost caused by less emissions of carbon dioxide are reported.

Keywords: fuel economy, heavy duty vehicles, driving cycle, global climate change.

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Dependence of Fuel Economy on Speed for two Heavy Duty Vehicles

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ABSTRACT

Some recommendations have been made that vehicles should travel at certain speeds in order to reduce their fuel consumption because gasoline and diesel are currently very expensive in many countries. There is also the menace of fuel shortages approaching the near future in some parts of the world. These recommendations are based on the fact that on the road the fuel economy of a vehicle increases while travelling at cruise speed without acceleration, as it is shown in this paper. Some of the vehicles on the road are the heavy-duty vehicles which transport people, food, medicine, minerals, gasoline, diesel, and many other goods to keep the economy of any country running. The vast majority of heavy-duty vehicles on the road in the world still move with diesel engines. In this paper it is demonstrated, for the cases examined with heavy duty vehicles, that the fuel economy of vehicles depends on several factors which include the load transported, the acceleration to reach cruise speed, the engine, the gearbox, the wheels, the final drive, the maximum driving speed of the vehicles and the slope of the roads. The reduction of fossil fuels consumption in road transportation also reduces the emision of carbon dioxide to the atmosphere, a greenhouse gas which contributes to global climate change. For some of the cases studied the carbon dioxide emissions are also calculated. Savings in fuel consumption in dollars by driving at the best constant speeds and the reduction in the environmental cost caused by less emissions of carbon dioxide are reported. The calculations in this paper have been carried out using UAMmero, a computer program developed at the Mexican Universidad Autónoma Metropolitana. The results are presented for two heavy duty vehicles with 455 HP and 200 HP engines respectively, moving in two parts of a driving cycle used by the United States of America Environmental Protection Agency and the National Highway Transportation and Safety Agency to certify compliance of heavy duty vehicles to the fuel consumption and carbon dioxide emissions regulations in that country, as well as for the case in which they move with constant speed.

I. INTRODUCTION

The current rapid increase in the demand for oil and its world production inferior to the COVID-19 pre-pandemic level has led to oil prices above $100 United States of America (US) dollars per barrel in the world during several weeks in the first quarter of the year of 2022. Consequently, the prices for gasoline and diesel in the US and in some countries of Europe have reached maximum prices above $5 US dollars per gallon. Nowadays, some countries consider reducing its dependence on Russian oil which is also impacting the price of oil-bearing products and could even lead to shortages of fuels for transportation in some European countries and others. On top of that, the possibility of attacks against petroleum installations, natural disasters in oil exporting countries and wars around the world cause uncertainty in the prices of petroleum. Therefore, there is the need of reducing the fuel consumption of the vehicles on the road; among these are the heavy-duty vehicles which transport people and goods necessary for most of the economic activities of all the countries. The heavy-duty vehicles are so important that when there are not enough heavy-duty drivers on the road or when

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they do not work, for any reason, there are shortages in food, fuels and other goods as how a few countries have experienced recently. Most of the heavy-duty vehicles on the road in the world move with diesel engines; cleaner fuels or electric or hybrid heavy duty vehicles are not yet available or affordable. Furthermore, some countries rely on fleets of old vehicles, like in Mexico where heavy-duty vehicles have an average age of 17 years. Recently, there have been recommendations stating that to save fuels and money in road trips, automotive vehicles should be driven at specific speeds. However, in this paper it is demonstrated, for the cases studied with heavy duty vehicles, that the fuel economy depends on several factors which include the load transported, the acceleration to reach the cruise speed, the cruise speed, the engine fuel consumption with respect to the revolutions per minute of the engine (rpm) and the slope of the roads. Since decades ago, many countries have had the goal of reducing their fossil fuel consumption in the transportation sector to increase their energy security because they do not produce enough oil (like most of the European countries and the US) or refined petroleum products because they do not have enough refineries (like Mexico since the year of 1990). Another very important reason to reduce fossil fuel consumption in road transportation is the concern of global climate change because the combustion of fossil fuels produces carbon dioxide (CO_2) emissions which is a greenhouse gas. Due to these and other concerns like the deterioration of the air quality, there are currently several efforts to regulate the fuel economy and the CO_2 emissions of new light and heavy-duty vehicles around the world, although not many countries have imposed good mandatory regulations on them. For example, in the US, a new regulation will mandate that the new fleet of automobiles and light trucks reach a Corporate Average Fuel Economy of 49 miles/gallon or 20.83 kilometers (km) per liter by the year 2026. In the European Union, Japan, Canada, and the US, among a few other places, federal regulations on those matters have been implemented for new heavy-duty vehicles. The Greenhouse Gas

Emissions Model (GEM) [1], a computer program, was created to test compliance of heavy-duty vehicles to the US regulations and VECTO [2], another computer program, is being developed to test those vehicles to the regulations in the European Union. In Mexico, UAMmero is being developed [3] with different programming schemes from those of GEM and VECTO to evaluate fuel consumption and CO_2 emissions of heavy-duty vehicles; although there is not yet a Mexican federal regulation on those two variables but only some governmental programs to increase the fuel economy of heavy-duty vehicles [4]. UAMmero is being developed using free software and it does not require proprietary software to run it. UAMmero has been developed in C language and shows many of its results graphically. Some results from UAMmero have been compared with those out of GEM [3]. Most of the results of UAMmero have been obtained for a driving cycle that the US Environmental Protection Agency (EPA) and the National Highway Transport and Safety Administration (NHTSA) use to certify heavy duty vehicles to fuel consumption and CO_2 emissions [1]. UAMmero also calculates the fuel consumption and CO_2 emissions of heavy-duty vehicles travelling in highways, although until now only a very few of these results have been published. In this work the fuel economy and CO_2 emissions are calculated for two different heavy-duty vehicles moving in two parts of a driving cycle starting from speed zero and reaching their cruise speed. One of the two vehicles has a 455 Horse Power (HP) engine and the other a 200 HP engine, the first of the vehicles corresponds to a Class 8 heavy duty vehicle and the second one to a Class 2b-5 heavy duty vehicle. Some other calculations in which the two vehicles move with constant speeds are also reported. The cost of the fuel and that of the environmental damage due to the CO_2 emissions are calculated in order to show the reductions in both by driving at certain speeds. In section 2 the vehicle dynamics and the driving cycle is presented, in section 3 the characteristics of the two heavy duty vehicles are explained, in section 4 the fuel economy and the

CO_2 emissions are reported and finally section 5 contains the conclusions.

II. VEHICLE DYNAMICS AND DRIVING CYCLE

2.1 Forces and torques

The vehicle dynamics is described by Equation 1 [3].

$$(M + m_i)a = \frac{T_e R_{eff}}{r_w} - F_a - F_p - F_r \# \qquad (1)$$

The vehicle moves in one direction. In Equation 1, F_a, is the aerodynamic force, F_p is the force due to the slope of the road, F_r is the force due to the friction of the wheels with the pavement of the road. M is the total mass of the vehicle including the load, m_i is the inertial mass of the vehicle. M and m_i are proportionated in kilograms (kg). a is the magnitud of the linear acceleration, r_w is the radius of one wheel (all the wheels have the same radius). T_e is the engine torque necesary to move the vehicle. R_{eff} is the effective ratio of the gear ratio of the gearbox being used by the vehicle in motion combined with the final drive ratio of the vehicle. In this work a heavy-duty vehicle with a 455 HP engine and 10 gear gearbox and a heavy truck with a 200 HP engine and 6 gear gearbox are analized. All the parameters of these two vehicles can be found in the user's guide of GEM 2010 [5] and in the software of GEM developed for the first phase of the regulation in the US. F_a, F_p, and F_r, are calculated using Equations 2, 3 and 4.

$$F_a = \frac{1}{2} c_{air} A_L \rho_a V^2 \# \qquad (2)$$

r_w =0.489 meters (m) for the 455 HP heavy duty vehicle and 0.378 m for the 200 HP heavy truck. The speed of the vehicle along the road, V, is given in meters per second (m/s), although in some results is reported in km/hr. In Equation 2, $c_{air} = 0.69$, is the aerodynamic coefficient for the 455 HP heavy duty vehicle and $c_{air} = 0.6$ for the

heavy truck. $\rho_a = 1.1845 \frac{kg}{m^3}$, is the air density. $A_L = 10.4\ m^2$, is the frontal area of the 455 HP heavy duty vehicle and $A_L = 9.0\ m^2$, for the 200 HP heavy truck.

$$F_p = Mg\sin(\theta) \# \qquad (3)$$
$$F_r = C_r Mg \cos\cos(\theta) \# \qquad (4)$$

The mass without load for the heavy-duty vehicle is of $14742\ kg$, the mass for the heavy truck without load is of $4407\ kg$. $g = 9.8066\ \frac{m}{s^2}$, is the acceleration of gravity. θ is the angle of inclination of the road. $C_r = 0.007205$ for the 455 HP heavy duty vehicle and $C_r = 0.0035$ for the 200 HP heavy truck. The frequency of rotation of a wheel, ω_w, is obtained from Equation 5.

$$\omega_w = \frac{V}{r_w} \# \qquad (5)$$

The frequency of rotation of the engine, ω_e (or rpm), is obtained from Equation 6.

$$rpm = \omega_e = R_{eff}\omega_w \# \qquad (6)$$

The relation between the speed of the vehicle and the rpm of the engine (ω_e) is given in Equation 7.

$$V = r_w\omega_w = \frac{r_w}{R_{eff}}\omega_e \# \qquad (7)$$

The engine torque, T_e, to move the vehicle is given in equation 8.

$$T_e = \frac{Fr_w}{R_{eff}} \# \qquad (8)$$

Where F is defined in Equation 9.

$$F = F_r + F_a + F_p + Ma + m_i a \# \qquad (9)$$

$F, F_r, F_a, F_p, Ma\ and\ m_i a$ are obtained in Newtons (N). T_e, is obtained in Newtons times meters (N-m). m_i, is defined in Equation 10.

$$m_i = \frac{I_{eff}}{r_w^2} \#\qquad(10)$$

In equation 10, I_{eff} is the effective moment of inertia. The inertial mass involves the rotating parts of the vehicle, like the wheels, the final drive, the clutch and the current gearbox gear used in moving the vehicle. As the vehicle moves, it uses different gears of the gearbox to accelerate or deaccelerate [3] and therefore the inertial mass changes. If the vehicle does not accelerate or deaccelerate there is no change of gears during the trip, although different speeds might require different gears. Different gears have different ratios and therefore R_{eff}, changes as the gears change during the motion of the vehicle. The changes of gears are considered instantaneous.

As the vehicle moves, the rpm and T_e change if the vehicle accelerates or deaccelerates, otherwise they remain constant. Once the rpm and T_e are calculated, the fuel consumption of the vehicle in kg/s is obtained using the engine fuel map which is a table of fuel consumptions for pairs of rpm and T_e. The instantaneous fuel consumption in kg per liter is calculated (considering a diesel density of 0.847 kg/liter), as well as the distance travelled. From the distance travelled and the fuel consumption, the fuel economy is obtained in km per liter (km/liter), because it is the distance travelled over the fuel consumed. The cost of the fuel for the trip is obtained by multiplying the price of a liter of diesel in US dollars by the amount of fuel consumed in liters. The amount of CO_2 emitted in kg is obtained by multiplying the number of liters of diesel consumed in the engine by 2.6 kg/liter, which is the amount of CO_2 emitted for a liter of diesel burned. The environmental cost of the CO_2 emitted is obtained by multiplying the amount of tons (thousands of kg) of CO_2 for the environmental cost of one ton of CO_2 emitted to the atmosphere, which in this work is taken as $12 US dollars.

2.2 Vehicle moving in the two highway parts of a driving cycle

The driving cycle which is used in GEM to certify heavy duty vehicles to fuel consumption and CO_2 emissions is a table of values of the speed of the vehicle with respect to time. The driving cycle consists of three parts; the speed for the first, second and third parts versus time is shown in Figure 1. The first part models the speed of the vehicle in an urban region. The second part simulates the speed of the vehicle in a highway with maximum speed of 55 miles/hr or 88.5139 km/hr. And the third part models the speed of the vehicle which moves in a highway with maximum speed of 65 miles/hr or 104.6074 km/hr. In the first part of the driving cycle, which is the urban region, the vehicle accelerates and deaccelerates constantly whereas in the second and third parts the vehicle starts with zero speed, and then advances with a constant acceleration until it reaches the maximum speed and thereafter advances at that speed for several minutes and finally deaccelerates up to zero speed. In this paper the calculation for the fuel economy and CO_2 emissions is carried out for the parts 2 and 3 of the driving cycle to show that the fuel economy also depends on the acceleration to reach a maximum speed. The calculation of the fuel economy is carried out for parts 2 and 3 of the driving cycle for the parts in which the vehicle accelerates and the parts in which the vehicle moves with the maximum speeds. The maximum speeds for the parts 2 and 3 of the driving cycles are target or objective speeds because they are not reached if the vehicle transports a heavy load or travels in a road with a steep slope; in these cases, the necessary torque to move the vehicle is larger than the maximum torque that the engine can provide. Therefore, in cases in which the necessary torque, T_e, to move the vehicle is larger than the maximum that the engine can provide, $T_{e,\,max}$, the vehicle acceleration is reduced to the one obtained with the maximum torque that the engine can provide; thus, the resulting maximum speed in which the vehicle moves becomes smaller than the target speed.
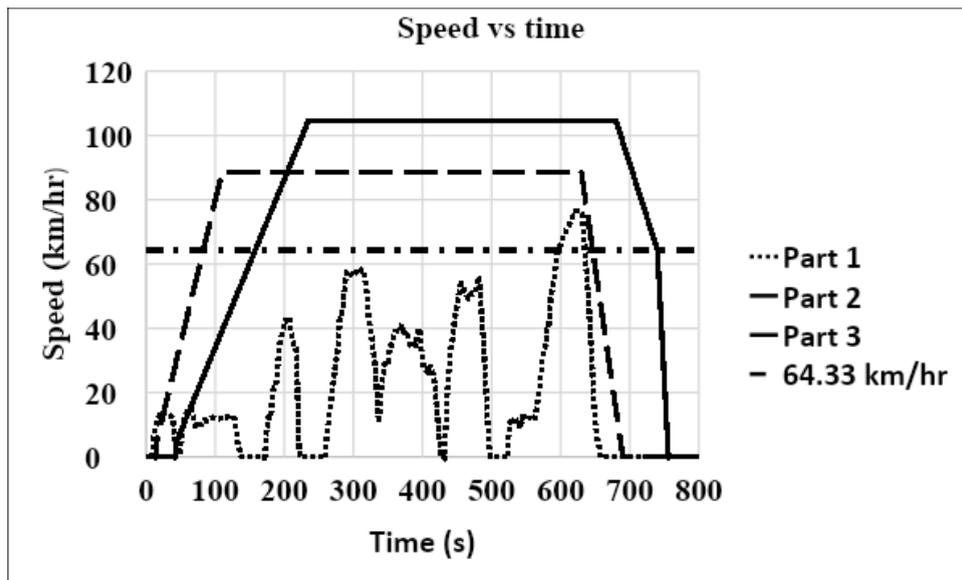
Figure 1: Target speed (km/hr) versus time (s) for parts 1, 2 and 3 of the driving cycle as well as a constant speed of 64.33 km/hr versus time (not part of the driving cycle).

2.3 Vehicle moving with constant speed

Calculations of the fuel economy and CO_2 emissions for the case in which the vehicle moves with constant speed all the time are also presented, see Figure 1 for the constant speed of 64.33 km/hr; although the results are presented for constant speeds from 4 up to 104.6074 km/hr. In these cases, the vehicle does not start moving from zero speed and the vehicle acceleration is zero all the time. In this case the necessary engine torque to move the vehicle is obtained from Equation 11 (because the acceleration is zero).

$$T_e = \frac{\left(F_r + F_a + F_p\right)r_w}{R_{eff}} \quad \# \quad (11)$$

UAMmero is run for the part 3 of the driving cycle to easily obtain the fuel economy for the constant speed cases. The rpm for any speed of the vehicle is calculated (Equation 7) and then the acceleration is set equal to zero in the calculation of the torque (Equation 11).

After obtaining the rpm and T_e, the fuel consumption is obtained from the array of the fuel map. In the cases of constant speed (no acceleration), the necessary torque to move the vehicle is smaller than in the case when the vehicle accelerates (for same values of the speed); therefore, the fuel consumption is smaller than in the cases in which the vehicle first accelerates to reach the maximum speed. Thus, the fuel economy is larger in the case of constant speed as it is shown in the results below.

III. CHARACTERISTICS OF THE HEAVY-DUTY VEHICLES

In this work the fuel economy and CO_2 emissions are calculated for a 455 HP heavy-duty vehicle and for a 200 HP heavy truck. The mass of the 455 HP heavy duty vehicle without load is of 14742 kg; with a load of 17236 kg, its total mass is of 31978 kg. The mass of the 200 HP without load is of 4407 kg and several loads are considered. The parameters for the engine, gearbox, clutch and wheels for the 455 HP heavy duty vehicle are given elsewhere [3][5]. The parameters for the engine, gearbox and wheels for the 200 HP heavy truck have been also proportionated elsewhere [5]. The fuel consumptions by the engines are provided by fuel maps, which were directly obtained for the two vehicles from the data of the first version of the software of GEM.

3.1 455 HP Heavy Duty Vehicle

The maxima of the maximum torque, $T_{e,max}$, the maximum power, $P_{e,max}$ (equal to 0.745699872* $T_{e,max}$*rpm), as well as for the specific fuel consumption (SC) for $T_{e,max}$ (SC_{max}), as a function

of rpm, proportionated by the 455 HP engine are: 2100 N-m (at rpm=1200 and rpm=1250), 455.26066 HP (at rpm=1800) and 0.0000505376 kg/(HP*s) respectively. The engine specific fuel consumption (SC) is obtained by dividing the fuel consumption over the engine power. The normalized values with respect to their maxima of $T_{e,max}$, $P_{e,max}$, and SC_{max}, are shown in Figure 2.
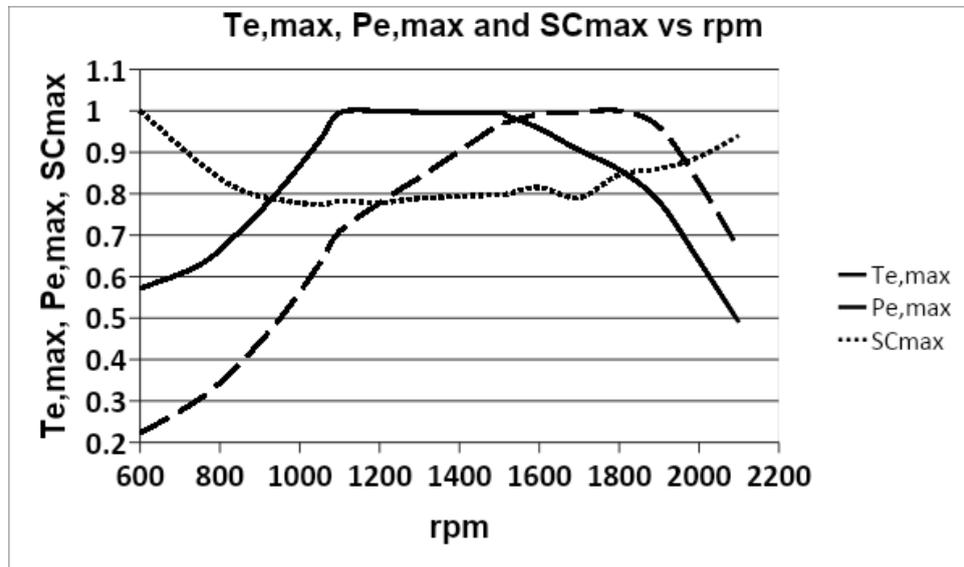

Figure 2: $T_{e,max}$, $P_{e,max}$ and the values of the specific fuel consumption for $T_{e,max}$ versus rpm, for the 455 HP heavy duty vehicle.

The range of values of rpm, are determined by the speed at which the vehicle travels, the values of the speeds at which the vehicle changes gears, the radius of the wheels, and by the values of the effective ratios of the relations of the gears (Equation 7) [3]. During the driving, the rpm used in moving the vehicle are located, most of the time of operation of the heavy duty vehicles, around the values which produce the maximum of the torque and the minimum of the specific fuel consumption; that is how the heavy duty vehicles are designed, to be driven around the maximum of the torque because of the heavy loads that they transport and in the region of the minimim of the specific fuel consumption.

3.2 200 HP heavy truck

The maxima of the maximum torque, $T_{e,max}$, the maximum power, $P_{e,max}$, as well as the specific fuel consumption for $T_{e,max}$, as a function of rpm, proportionated by the 200 HP engine are: 7300 N-m (at rpm=1300, 1500, 1600 and 1800), 200.25964 HP (at rpm=2000) and

0.0000938264 kg/(HP*s) respectively. The normalized values with respect to their maxima of $T_{e,max}$, $P_{e,max}$, and SC_{max}, are shown in Figure 3.
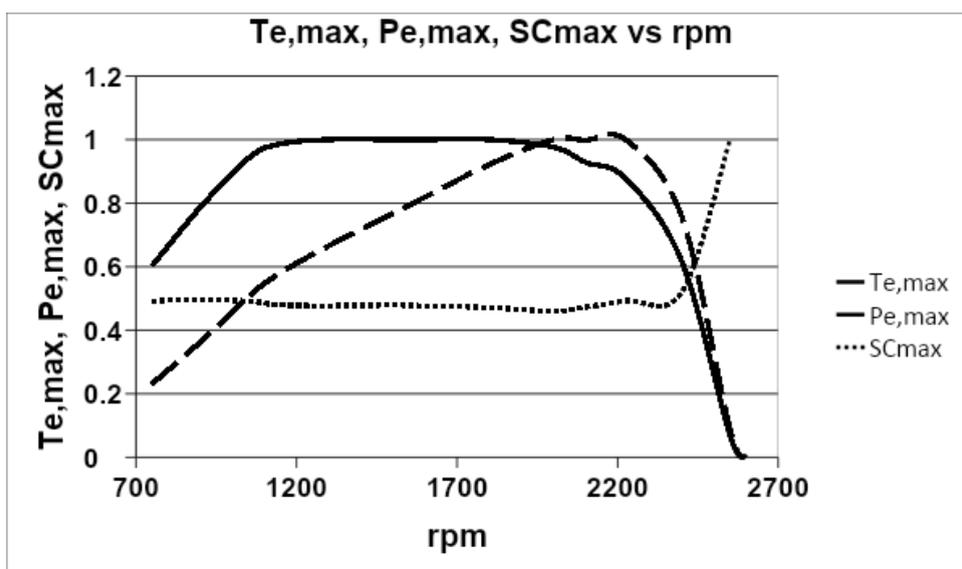
Figure 3: $T_{e,max}$, $P_{e,max}$ and the values of the specific fuel consumption for $T_{e,max}$ versus rpm, for the 200 HP heavy truck.

IV. FUEL ECONOMY

In this section the results for fuel economy for the 455 HP heavy duty vehicle and for the 200 HP heavy truck are presented.

4.1 455 HP heavy duty vehicle moving in a road with zero slope

In this section the results for the fuel economy for the 455 HP heavy duty vehicle moving in parts 2 and 3 of the driving cycle and with constant speeds are compared. The T_e is obtained from Equation 8 which depends on F (Equation 9). In Figure 4 the values of F_a, F_r, Ma and $m_i a$ are shown as a function of the speed for the 455 HP heavy duty vehicle, for 0° of the inclination of the road, M= 31978 kg and the part 3 of the driving cycle; F_p is not shown because is equal to zero.
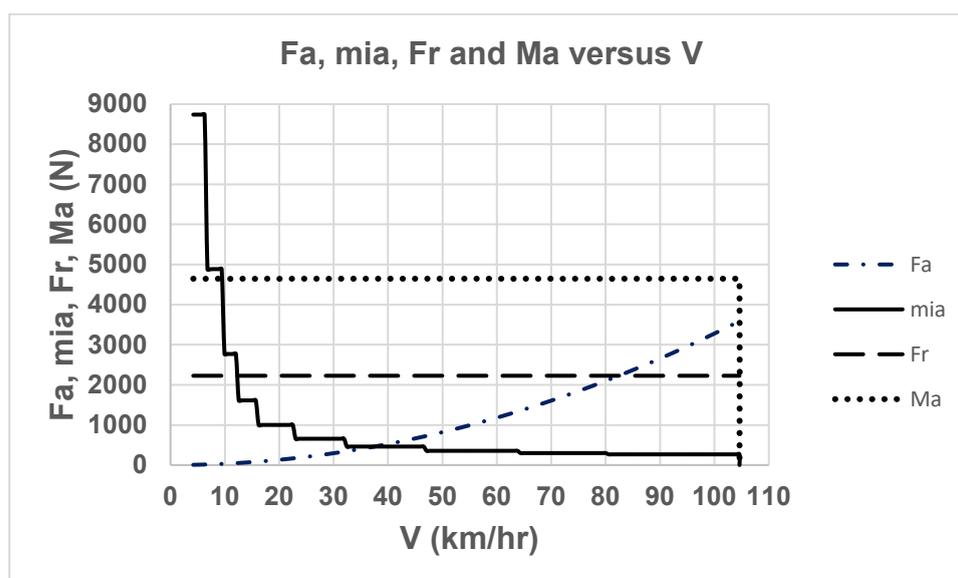

Figure 4: F_a, F_r, Ma and $m_i a$ versus the speed of the vehicle for the case of 0° of inclination of the road, M= 31978 kg and the part 3 of the driving cycle.

F_a, the aerodynamic force increases cuadratically as the speed increases as it is seen in Figure 4. Ma is constant because, a, the acceleration is constant and larger than zero ($a = 0.1453 \frac{m}{s^2}$) except in the part in which the vehicle travels at constant speed of 104.6074 km/hr; at this constant speed the acceleration is zero and Ma becomes zero. F_r is constant because it does not depend on the speed. The inertial mass, m_i, changes as the vehicle accelerates and changes gears because they have different ratios. In this case, m_i decreases as the vehicle changes gears from the first to the tenth. $m_i a$ is the value of m_i multiplied by the constant value of a until the vehicle starts moving with constant speed, and in this last part $m_i a$ is equal to zero because the acceleration is zero.

For the part 2 of the driving cycle, the maximum speed reached is of 86.6081 km/hr; a little less than the target speed of 88.5139 km/hr. F_r and F_a have the same values as for the part 3 of the driving cycle up to the maximum speed which in this case is of 86.6081 km/hr; Ma and $m_i a$ have the same shape as for the case of the part 3 of the driving cycle but their values are larger in the part in which the acceleration is constant and larger than zero, because in this case $a = 0.2459 \frac{m}{s^2}$, except very close to the part of constant speed because the needed torque for those values of the speed is larger than $T_{e,\,max}$ and therefore the acceleration has to be reduced which leads to a smaller speed than the target speed of 88.5139 km/hr. F_p is also zero because the road has an inclination of 0°.

For the case in which the vehicle travels at any constant speed during its whole trip, the values of F_a, F_r, F_p, Ma and $m_i a$ would be represented by a single points in Figure 4, because the vehicle travels at just one (constant) speed. And in this case, both Ma and $m_i a$ are equal to zero because the acceleration is zero. F_p is zero because the inclination of the road is zero. F_r and F_a have the

values that they have for part 3 of the driving cycle for the same value of the speed. The results below are obtained not just for one value of a constant speed but for constant speeds from 4 up to 104.6074 km/hr.

In Figure 5 the value of F is shown as a function of the speed for the two parts of the driving cycle and for the case in which the vehicle moves with constant speed (for a range of constant speeds from 4 to 104.6074 km/hr). For the case in which the speeds are constant from 4 to 104.6074 km/hr their values of F are smaller than the value of F for the two parts of the driving cycle in which the vehicle accelerates, as it can be seen in Figure 5, because the two parts of the driving cycle include Ma and $m_i a$, which are zero in the cases of constant speed. Thus, F is smaller (for the same value of the speed) for the case in which the vehicle travels at constant speed. Also, the value of F is smaller for the part 3 of the driving cycle when the vehicle is accelerating, than for the part 2, because the acceleration is smaller for the part 3 as it can be seen in Figure 5. That is, if the vehicle accelerates, F is larger for the cases in which the acceleration is larger (for the same value of the speed). For the case of constant speed ($F = F_r + F_a + F_p$), the larger the value of the constant speed the larger the value of F as it is seen in Figure 5, because F_a depends on the square of the speed (F_r and F_p do not depend on the speed). For the parts 2 and 3 of the driving cycle there are jumps in the values of F because the values of the inertial mass of the vehicle change (and are discontinuous) as the vehicle changes gears; however, there are no jumps for the case of constant speed because the inertial mass does not contribute to F. When the vehicle travels at constant speed at the end of the parts 2 and 3 of the driving cycle, the value of F is larger for part 3 because the constant speed (104.6074 km/hr) is larger than that for part 2 (86.6081 km/hr), therefore F_a is larger and consequently F will be larger for part 3 of the driving cycle. The values of F for parts 2 and 3 when the vehicle travels at constant speeds, 86.6081 and 104.6074 km/hr respectively, are the same as the values of F for the corresponding values of the speed for the

cases in which the vehicle travels at constant speed during all the trip at those two particular values of the speed. That is why the values of F of the parts 2 and 3 intersect the values of F for the case of the vehicle traveling at constant speed. For parts 2 and 3 of the driving cycle the term $m_i a$ is the largest for the smallest speeds, and for larger values of the speed the term Ma is the largest and for the largest speeds F_a is the largest, because it has a dependence of V square.
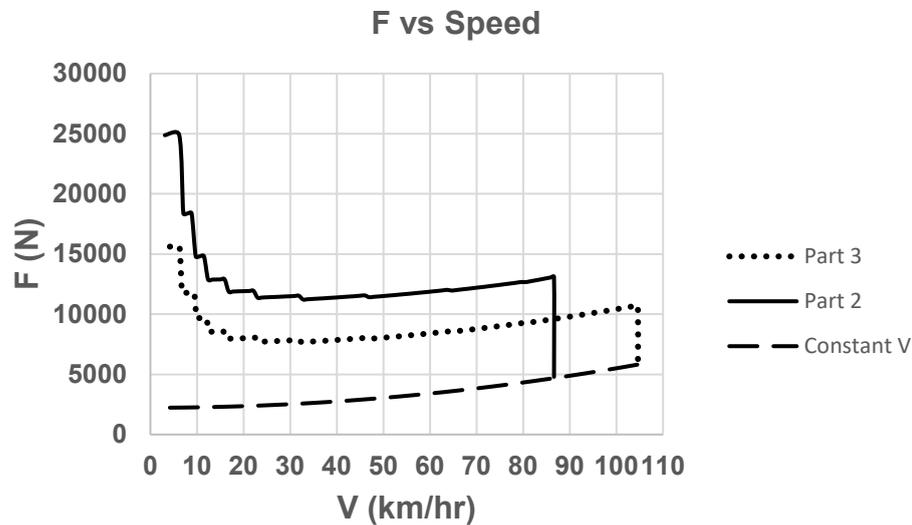
F vs Speed

Figure 5: Value of $F = F_r + F_a + F_p + Ma + m_i a$ versus speed for parts 2 and 3 of the driving cycle and for the case in which the speed is constant (for constant values of the speed from 4 up to 104.6074 Km/hr).

Figure 6 shows the engine torque, T_e, which is the torque that the engine provides for the vehicle to move and that it is equal to F times the radius of a wheel, r_w, divided by R_{eff}. For the same speed, R_{eff} is the same for the cases of the two parts of the driving cycle and the case of the vehicle moving at constant speed. Thus, for the same value of the speed, if F is larger for the two parts of the driving cycle than for the case of constant speed, T_e will be also larger for those two parts than for the case of constant speed. And if F is larger for the part 2 than for the part 3 of the driving cycle then T_e will be larger for the part 2.

As it is noticed in Figure 6, T_e, has jumps because it is obtained by dividing F by R_{eff}; and R_{eff} is discontinouos as a function of the speed and its value is smaller for larger values of the speed. As T_e is obtained by multiplying F by the radius of the wheel, r_w, the engine torque depends on that radius and therefore the fuel economy will also depend on the size of the wheel.
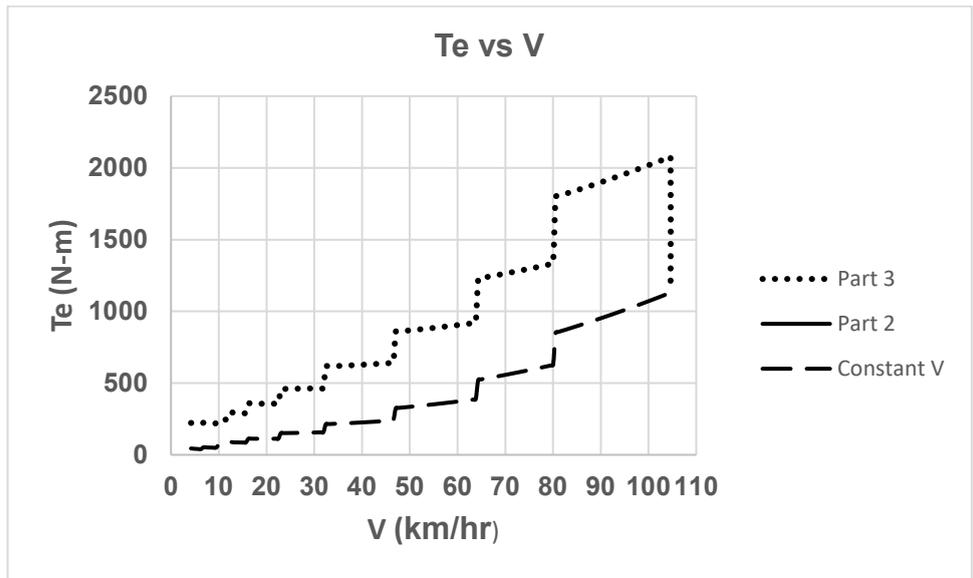
Figure 6: Engine torque, T_e, versus speed of the vehicle for parts 2 and 3 of the driving cycle and for the case in which the speed is constant (for constant values of the speed from 4 up to 104.6074 Km/hr).

The engine fuel consumption for a few pairs of rpm and T_e is shown in Figure 7. The values for the fuel consumption were taken directly from the first version of the GEM software developed by the US EPA. In the table of the US EPA there are 17 times 31 values of fuel consumption and then an interpolation is carried out to obtain the values of the fuel consumption for any value in the range of rpm from 600 up to 2200 and in the range of the torque from 0 up to 3000 N-m. The fuel consumption obtained by interpolation using the 31 times 17 table for rpm=1267.3064 and rpm=1498.0440 for several values of T_e are provided in Figure 7.
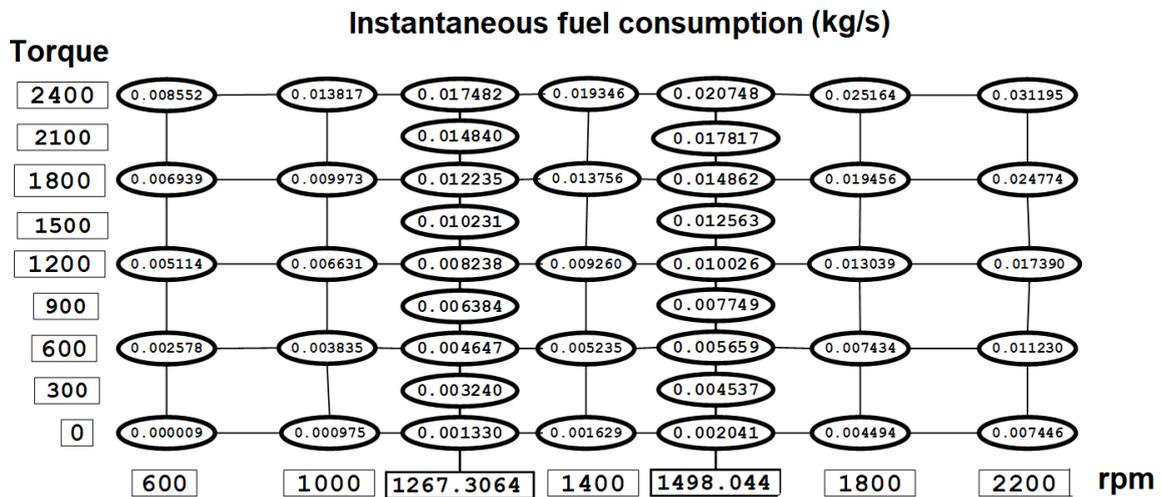

Figure 7: Instantaneous engine fuel consumption in kg/s for pairs of the engine torque and rpm.

Figure 8 shows the instaneous fuel consumption of the engine versus the speed of the vehicle. For the same rpm the instaneous fuel consumption increases as the engine torque increases, therefore for the same value of the speed (see Equation 7) the fuel consumption will be larger for larger values of the engine torque. Thus, for the same speed, the fuel consumption for the two parts of the driving cycle will be larger (because the engine torques are larger for them) than for the case of constant speed, as it can be seen in Figure 8. For the case of constant speed, as the torque is larger

for larger speeds, the fuel consumption will increase (in average) if the vehicle moves at larger speeds.
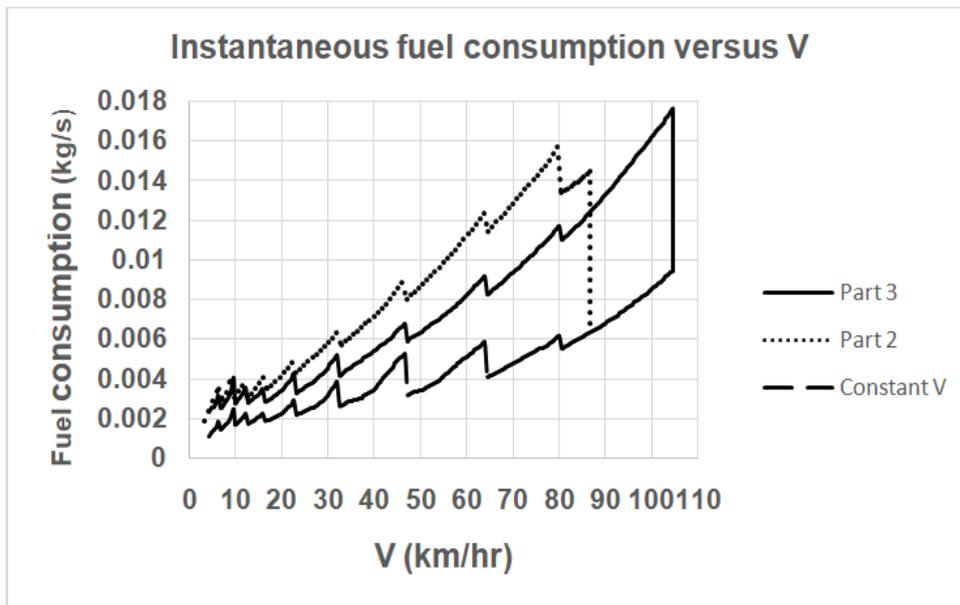

Figure 8: Instantaneous fuel consumption for parts 2 and 3 of the driving cycle and for the case in which the speed is constant (for constant values of the speed from 4 up to 104.6074 Km/hr), versus the speed of the vehicle.

Figure 9 shows the results for the fuel economy versus the speed of the vehicle for the parts 2 and 3 of the driving cycle and for the cases of constant speed (for constant values of the speed from 4 up to 104.6074 Km/hr). For speeds less than 35 km/hr, the fuel economy increases (in average) as the vehicle increases its speed with some sudden jumps when there is a change of gears in the case of the parts of the driving cycle in order to increase the speed of the vehicle, and when different gears are used for different values of the constant speed in the case in which the vehicle travels with constant speed during all the trip. The largest fuel economy is reached for the speed of 64.33 km/hr and it is of 3.71 km/liter; it is at this speed in which the vehicle travels at constant speed and therefore there is no acceleration of the vehicle and the needed torque to move the vehicle is smaller (see Equation 11). The fuel economy for the vehicle moving in the part 3 of the driving cycle is larger than for the case of part 2 because the acceleration in the part 3 of the driving cycle is smaller than for the part 2 (as it can be seen in Figure 1). The results of parts 2 and 3 show that the fuel economy depends on the acceleration of the vehicle and comparing these two cases, the conclusion is that when the acceleration is smaller the fuel economy is larger. The results of part 2 and 3 of the driving cycle show that after the vehicle stop accelerating, when the vehicle travels at constant speed the fuel economy increases appreciably and that the fuel efficiency for the case of part 2 of the driving cycle is larger than for the part 3 of the driving cycle. The last result is due to the fact that the final constant speed in the part 3 of the driving cycle (104.6074 km/hr) is larger than in the part 2 (86.6081 km/hr) and therefore F_a, the aerodynamic force is larger and then the needed torque to move the vehicle is larger which leads to a larger fuel consumption. When the vehicle reaches its highest speed (86.6081 km/hr in case of part 2 and 104.6074 km/hr in case of part 3 the vehicle travels in the 10th gear of the gearbox in both cases.
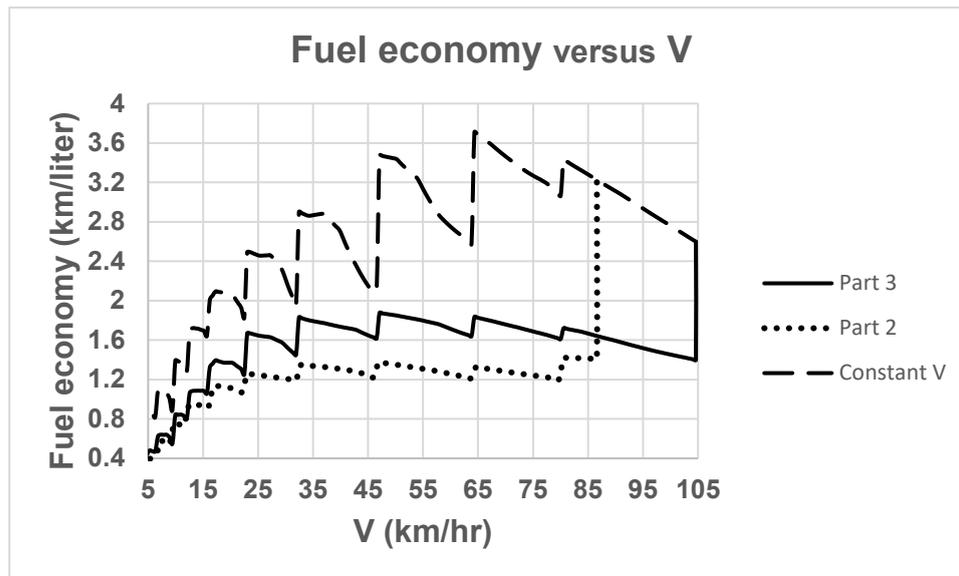
Figure 9: Fuel economy (km/liter) versus the speed of the vehicle for the 455 HP heavy duty vehicle moving in parts 2 and 3 of the driving cycle and for the cases of constant speed. Load 17236 kg.

The fuel economy has a maximum (as it is seen in Figure 9) even though the fuel consumption increases with the speed because is the ratio of the distance travelled (which increases with the speed) over the fuel consumption. Notice that when the speed is equal to 86.6081 km/hr the fuel economy of part 2 of the driving cycle and that of constant speed are the same (and equal to 3.22515102 km/liter) as it should be, because in both cases at that speed the vehicle is travelling at constant speed. Likewise, for the part 3 of the driving cycle and the case of constant speed at the speed of 104.6074 in which both have a fuel economy of 2.59914436 km/liter. Definitely travelling at constant speed increases the fuel economy and the best constant speed in this case is of 64.44 km/hr.

For a load of 17.236 tons and zero slope of the road, the results in Figures 6, 7 and 8 explain the fuel economy obtained in Figure 9.

For the part 2 of the cycle, UAMmero also provides the following results for the trip: 4.862631 liter of fuel consumed. 14.752320 km of distance travelled. 0.012643 tons of CO_2 emitted. 3.0338149 km/liter of fuel economy. 0.329618 liter/km. 0.019124 liter/(ton*km), the ton refers to the transported load. 49.721919 g/(ton*km) of CO_2, the ton refers to the transported load. 5.6372 dollars (at 1.1593 dollars/liter) of payment for fuel. 0.151714 US dollars for environmental damage (at 12 US dollars the ton de CO_2).

For part 3 of the driving cycle: 6.808530 liter of fuel consumed. 17.387621 km of distance travelled. 0.017702 tons of CO_2 emitted. 2.55380223 km/liter of fuel economy. 0.391573 liter/km. 0.022718 liter/(ton*km), the ton refers to the transported load. 59.067700 g/(ton*km) of CO_2, the ton refers to the transported load. 7.8931 dollars of payment for fuel. 0.212426 US dollars for environmental damage.

On the other hand, driving at a constant speed of 64.33 km/hr the fuel economy is of 3.71 km/liter. For a distance of 14.752320 km (the distance travelled in the part 2 of the driving cycle) the fuel consumption would be of 3.97636658 liters and the cost of the trip would be of only 4.6098 dollars (a saving of 18.225 %). There would be also a reduction of 18.225 % in the CO_2 emissions.

Driving at a constant speed of 64.33 km/hr, for a distance of 17.387621 km (the distance travelled in the part 3 of the driving cycle) the fuel consumption would be of 4.6866903 liters and the cost of the trip would be of only 5.4333 dollars (a saving of 31.1640 %). There would be also a reduction of 31.1640 % in the CO_2 emissions.

Therefore, the recommendation would be to maintain an appropriate constant speed when

travelling in highways; although it is necessary to accelerate to reach the constant speed.

4.2 200 HP heavy truck

For the 200 HP heavy truck several results are presented by changing the transported load as well as the slope of the road.
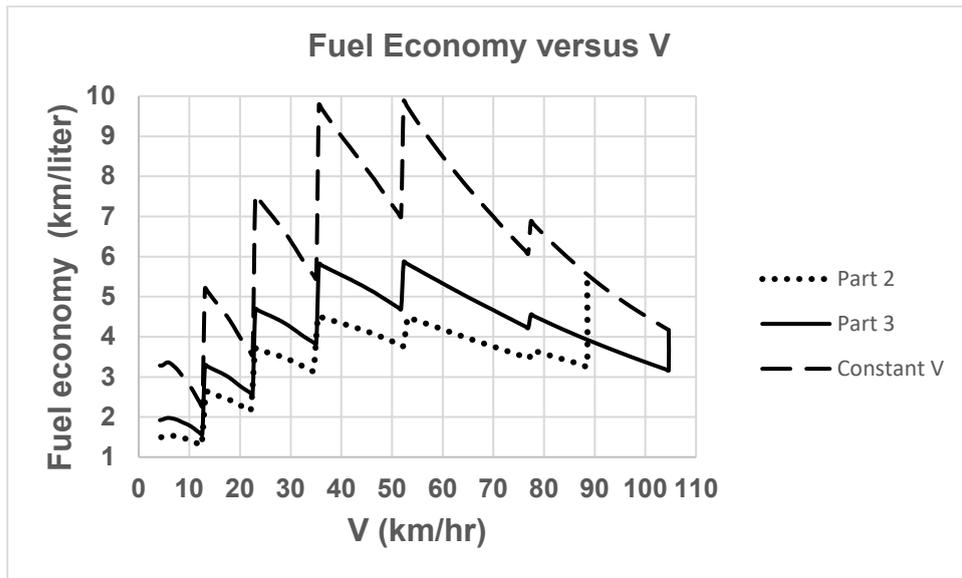
4.2.1 Results for the fuel economy for parts 2 and 3 of the driving cycle and for the case of constant speed (for constant values of the speed from 4 up to 104.6074 Km/hr) for 0° of inclination of the road

In Figure 10 the values of the fuel economy as a function of the speed are presented for a transported load of 2 tons, and 0° of inclination of the road, for the two parts of the driving cycle and the case of constant speed. As for the case of the 455 HP heavy duty vehicle the fuel economy is larger for the case in which the vehicle does not accelerate at any moment because it travels at constant speed. The maximum fuel economy is of 9.88171586 km/liter at the constant speed of 52.303608 km/hr. The fuel economy is better for the case of constant speed, as it was seen in the previous section, because the engine torque in that case is smaller than the corresponding engine torque for the two parts of the driving cycle (for the same speed of the vehicle) because the acceleration of the vehicle is zero. And the fuel economy for the part 3 of the driving cycle is larger than for the part 2 (for the interval of speeds in which the vehicle accelerates) because the acceleration of the vehicle is smaller in the part 3 of the cycle.

For the part 2 of the cycle, the following results are obatined: 2.648253 liter of fuel consumed. 14.752320 km of distance travelled. 0.006885 tons of CO_2 emitted. 5.57059617 km/liter of fuel economy. 0.179514 liter/km. 0.089757 liter/(ton*km), the ton refers to the transported load. 233.368657 g/(ton*km) of CO_2, the ton refers to the transported load. 3.0701 dollars of payment for fuel. 0.082625 US dollars for environmental damage.

For part 3 of the driving cycle: 3.931462 liter of fuel consumed. 17.387621 km of distance travelled. 0.010222 tons of CO_2 emitted. 4.42268484 km/liter of fuel economy. 0.226107 liter/km. 0.113053 liter/(ton*km), the ton refers to the transported load. 293.939057 g/(ton*km) of CO_2, the ton refers to the transported load. 4.5577 dollars of payment for fuel. 0.122662 US dollars for environmental damage.

On the other hand, driving at a constant speed of 52.303608 km/hr the fuel economy is of 9.88171586 km/liter. For a distance of 14.752320 km (the distance travelled in the part 2 of the driving cycle) the fuel consumption would be of 1.49289053 liters and the cost of the trip would be of only 1.7307 dollars (a saving of 43.6272 %). There would be also a reduction of 43.6272 % in the CO_2 emissions. Driving at a constant speed of of 52.303608 km/hr, for a distance of 17.387621 km (the distance travelled in the part 3 of the driving cycle) the fuel consumption would be of 1.75957508 liters and the cost of the trip would be of only 2.0399 dollars (a saving of 55.2428 %). There would be also a reduction of 55.2428 % in the CO_2 emissions. Therefore, the recommendation would be to maintain an appropriate constant speed when travelling in highways; although it is necessary to accelerate to reach the constant speed.

Dependence of Fuel Economy on Speed for Heavy Duty Vehicles

Figure 10: Fuel economy (km/liter) for the two parts of the driving cycle and for constant speed (for constant values of the speed from 4 up to 104.6074 Km/hr) versus speed, for the 200 HP heavy truck, zero slope and 2 tons of load.

The next results in the rest of this section correspond to the vehicle moving with constant speed.

4.2.2 Constant speed, 0° degrees of inclination of the road and different values of the transported load

The results for the fuel economy versus the speed for the 200 HP heavy truck for constant speeds from 4 to 104.6074 km/hr for different values of the transported load and zero slope are presented in Figure 11. In this case the value of F is given by Equation 11 for $\theta = 0°$ and the only term which depends on the load is $F_r = C_r Mg$, where M is the sum of the masses of the vehicle and the load. The increment of the load from 0.1 to 5 tons does not affects significantly the fuel economy of the vehicle for the values of the constant speeds considered.
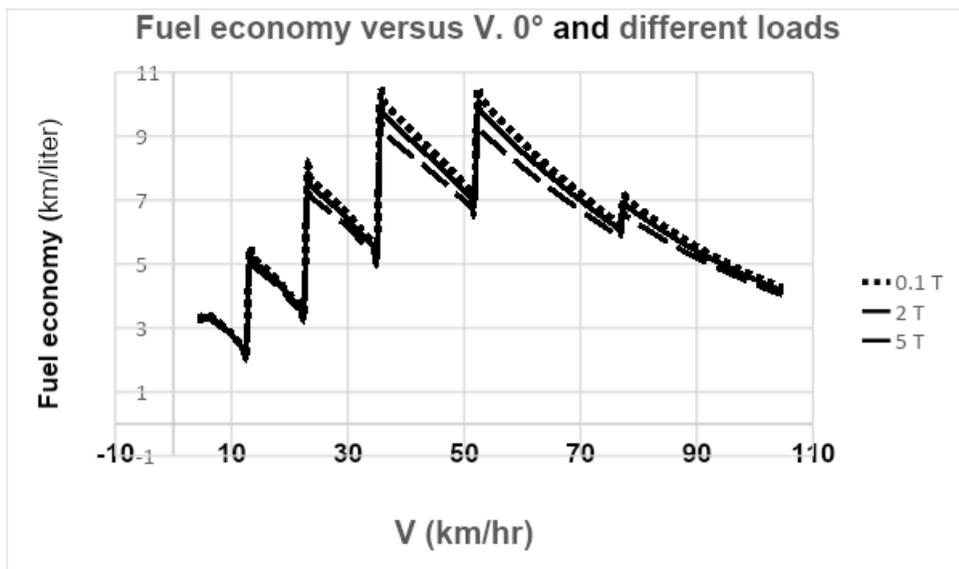
Figure 11: Fuel economy for the 200 HP heavy truck with different loads, zero slope and moving with constant speed (for constant values of the speed from 4 up to 104.6074 Km/hr). The masses of the loads are 0.1, 2 and 5 tons.

4.2.3 Constant speeds, 2 tons of transported load and different degrees of inclination of the road

The F_p force becomes the largest term in Equation 11 for some values of the inclination of the road. A large value of F_p results in a very large value of the necessary torque to move the vehicle that for some values of the speed results larger than $T_{e,\,max}$; therefore, even though the vehicle does not accelerate, the maximum constant speed at which the vehicle can move has a limit. The maximum value of the vehicle constant speed is that which results in a torque equal than the maximum torque that the engine can provide for that speed, as it is shown in Figure 12.

In Figure 12 are shown the values of the torque, versus the speed for the 200 HP heavy truck which transports 2 tons of load and which travels in roads with different inclinations. The maximum values of the torque that the engine can provide, $T_{e,max}$, versus the speed are also plotted. It can be noted that the maximum constant speed at which the vehicle can travel occurs when the engine torque, T_e, necessary to move the vehicle intersects the curve of $T_{e,max}$.
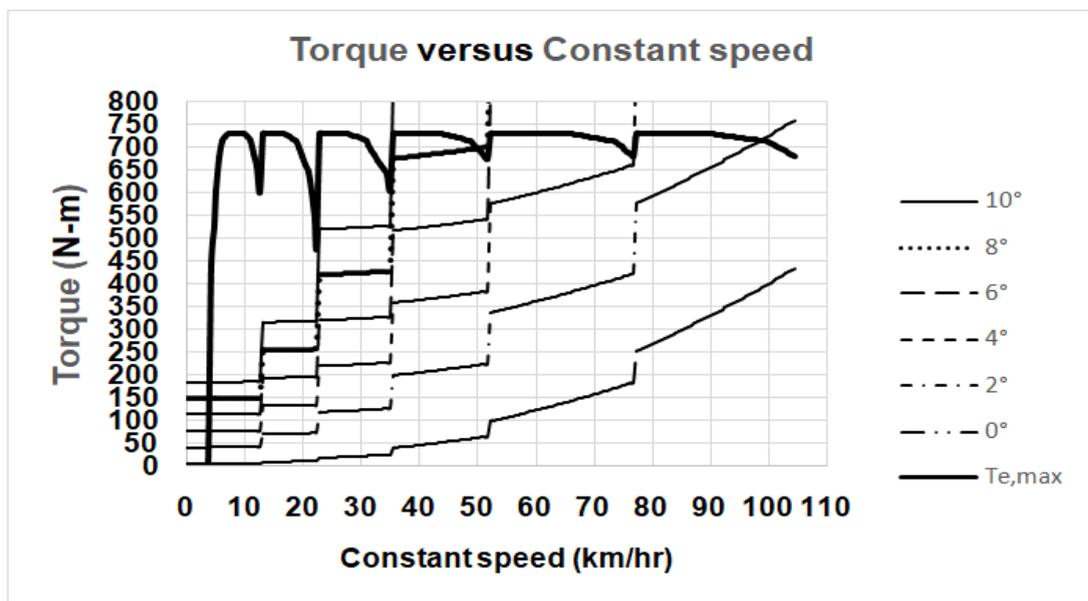

Figure 12: Maximum torque, $T_{e,max}$, and necessary torque, T_e, to move the 200 HP heavy truck with 2 tons of load in a road with different inclinations versus the constant speed of the vehicle.

The results for the fuel economy for the 200 HP heavy truck for a transported load of 2 tons and different values of the inclination of the road are presented in Figure 13. As the inclination angle of the road increases, the maximum constant speed in which the vehicle can move is smaller and the decrement in the values of the fuel economy is large. As it can be seen in Figure 13, travelling at constant speeds in a road with inclination of 10° results in a fuel efficiency around one tenth of the one reached when travelling at constant speed of 52.303608 km/hr in a road with 0°. This implies that the CO2 emissions in a trip in a road with an inclination of 10° will emit 10 times the CO_2 emissions than travelling in a road with 0° with a speed of 52.303608 km/hr. The trip in the steep road would be ten times more expensive than the trip in the flat road travelling at a speed of 52.303608 km/hr.
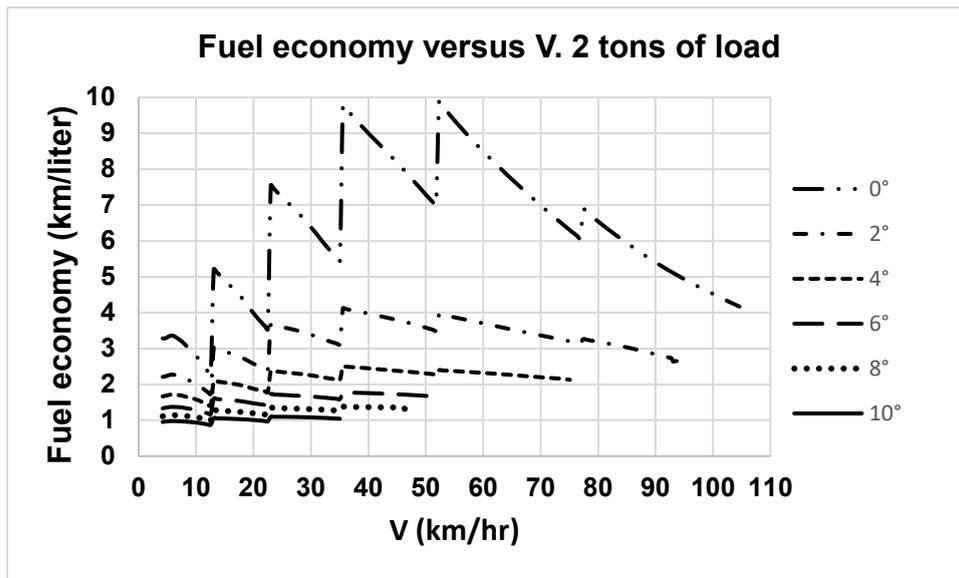

Figure 13: Fuel economy when the vehicle with two tons of load moves with constant speed on a road with different slopes

The recommendation of driving at constant speed can be done for driving in highways because in urban regions vehicles accelerate and deaccelerate constantly because of the traffic lights and many vehicles on the streets.

V. CONCLUSIONS

There are considerable savings in fossil fuels and an apreciable reduction of CO_2 emissions by driving at certain speeds and accelerations depending on the vehicle being driven, the engine, final drive, gearbox and wheels of the vehicle, the loads being transported and the slope of the roads. Driving at some constant speeds reduces the fuel consumption although those speeds are reached after accelerating the vehicle starting from a low speed. To maximize the savings, technical training of heavy-duty vehicle drivers is necessary. However, even drivers of passenger vehicles should be aware of the benefits of knowing that it is posible to save fuel if they consciously and purposely drive at the best speeds according to the routes they travel. In any case, the recommendation for any driver is: know your vehicle. Besides, the reduction in fuel and CO_2 emissions increase the energy security of the countries and the care of the global environment.

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