Modeling and Predicting Vehicle Performance in the Pre-design Phase

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Modeling & Predicting Vehicle Performance in the Pre-design Phase

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1 Introduction

Piston engines are the largest group of thermodynamic heat engines in use today. It is used in many different applications, it's found in all kinds of transportation, from a small size motor vehicle to aircraft.The reason of this wide use of those engines is their high energy convergence efficiency, and the high fuel to energy ratio they provide.There are two main types of piston engine: the spark-ignition engine and the diesel engine. The diesel engine is more efficient but it also generates more pollution. There are also two common engine cycles: the two-stroke cycle and the four-stroke cycle. It should be stressed that many prospective studies suggest that up to 60% of the cars will still use piston engines as main power source in 2050.

2 Project Goal

The goal of the project is to model and predict the performances of a vehicle in the pre-design phase. Various parameters will be studied to measure their influence on the chosen vehicle's performance.The vehicle chosen is the diesel car number 11 with the diesel engine 1 and normal gearbox. This choice corresponds to group code 33.

3 Maximum acceleration of first gear

In this part, the goal is to study the maximum acceleration of the first gear as function of the gear ration L1. Several assumptions have to be taken into account:
-To simplify the computations, express the ratio as the total ratio from engine speed to vehicle speed and make it vary between 0 and 10 km/h/(rpm/1000).
-The computations are performed at maximum torque and at an engine rotation speed of 2000 rpm.
-The clutch is assumed to be completely closed

3.1 General Equations for computation

The basic equation for the longitudinal vehicle dynamic is:

$$\Sigma Fext = m.\gamma \tag{1}$$

Fext are the external forces applied on the vehicle, gamma is the vehicle acceleration (m/s2), and m is an equivalent mass given by:

$$m(kg) = mvehicle(kg) + inertiaeq.wheel(kg) + inertiaeq.engine(kg) \tag{2}$$

Equivalent masses of inertia are used, i.e. inertiaeq.wheel and inertiaeq.engine to transfer the rotation inertia of the wheels and engine to a linear inertia in order to simplify the computation: having m_vehicle=1050, we have to add 100 Kg taking into account mass of the passenger. So we get a total mass of 1150Kg.

$$inertiaeq.wheel(kg) = 0,033.mvehicle(kg) \tag{3}$$

$$inertiaeq.engine(kg) = inertiaengine(kg.m2).(\frac{120\pi}{L(km/h/(rpm/1000))})^2 \times \eta_{GB} \tag{4}$$

where GB is the efficiency of the gear box (see vehicle data), L is the overall engine to wheel ratio, and inertiaengine is the inertia of the engine (see engine data). The equivalent mass of the engine inertia is only taken into account when clutch is closed. To better understand, this conversion, take for example when the vehicle accelerates, wheel spins faster considering:

$$\Sigma J_{wheel}\frac{d\omega}{dt} = T. \tag{5}$$

Increasing the rotation speed of the wheel thus requires a torque. The use of a equivalent linear inertia simplifies the computations as the torque required to increase the rotation speed of the wheel does not have to be computed. The external forces are

$$\Sigma Fext = Fr - Faero - Ftire - Fslope \tag{6}$$

where the engine force Fr is given by

$$Fr = \frac{T_{wheel(Nm)}}{R_{tire(m)}} = \frac{120.\pi.T_{engine(N.m)}.\eta GB}{L_{(km/h/(rpm/1000))}} \tag{7}$$

the aerodynamic force acting agains the vehicle is given by:

$$F_{aero} = \frac{1}{2}\rho(kg/m^3).S(m^2).C_x.V^2(m/s) \tag{8}$$

hacving the following variables as follows :

- ρ is the air density given to be 1.21 kg/m$\hat{3}$
- S.Cx is the surface area of the car undergoing this aerodynamic force (surface in contact with air) it is given in our case to be 0.65m$\hat{2}$
- V is the speed of the vehicle

Speed V of the vehicle can be computed as follows

$$V(m/s) = \frac{L(\frac{km/h}{rpm/1000}).\frac{N(rpm)}{1000}}{3.6} \tag{9}$$

the friction forces on the tires is:

$$F_{Tire} = m_{vehicle}(Kg).g(m/s^2).(0.1).C_{rr}.cos() \tag{10}$$

Knowing that Crr is the coefficient of the tires given in this case to be 8.5Kg/t and is the slope
the force due to the slope is given by :

$$F_{sloe} = m_{vehicle}.g(m/s^2).sin() \tag{11}$$

where is the slope angle.

3.2 Matlab Results

The equations discussed in part 3.1, are implemnted as Matlab code to plot the maximum acceleration as function of first gear ratio.The maximum acceleration obtained is 7.92 m/s$\hat{2}$ and the acceleration of the first gear is about 6.639. The result obtained are shown in figure1

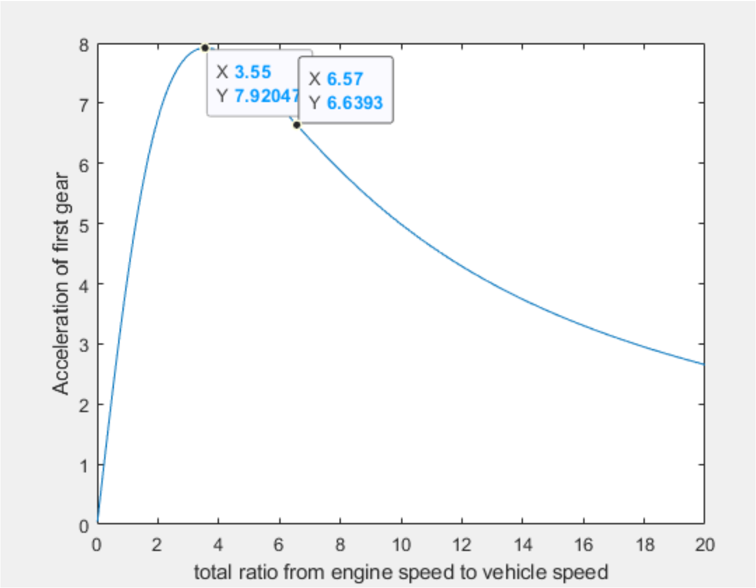


Figure 1: Acceleration of first gear

3.3 Conclusions

After the obtained results, some conclusions can be discussed here:

- The value of engine force decreases as the ratio of the gears increases. The engine inertia is high at low gear ratio values, this means that high force is needed to make the vehicle move.
- The aerodynamic force is proportional to vehicle speed, which is proportional for the gear ratio, so at high gear ratios, this force has to be taken into consideration

4 Acceleration from 80 to 120 km/h

The aim of this section is to compute the time required for for the vehicle to accelerate from 80 to 120 km/h in the 5th gear ratio for the three types of gearbox: Normal, short and long.

- L5shortt=37.93
- L5normal=42.15
- L5long=46.36

4.1 Computaions

MATLAB was used to calculate the time required to reach 120 km/h starting from 80 km/h. The equations mentioned in section 3.1 were used in addition to more equations in order to give approximate results for the for the acceleration time .
to get the equivalent mass of the system, equation (2) was used taking into consideration the different values of the ratio L5 for each time

to calculate the regime of the engine at a certain vehicle speed , equation (9) was used for different values of L5 .
To calculate the external forces ,equation (6) was used .
To calculate the acceleration , equation (1) was used.
to get the velocity of the vehicle for a time step of 0.25 (s), the following equation was used:

$$V = at + V_0 \tag{12}$$

Where V is the vehicle's velocity , a the instantaneous acceleration of the vehicle , t is the time step 0.25 (s) , and V0 is the velocity at the previous time step.
For each time step, starting from a velocity of 80 km/h, the same quantities are recalculated and the new velocity is calculated until a value of 120 is reached.The results found are shown in the following table:

4.2 Results

Matlab code was implemented to calculate the needed time to accelerate from 80 to 120km/h, the results are shown in the following table1

	Long	normal	short
Gear ratio	46.3597	42.1452	46.3597
time needed	45.25	37.75	32.5

Table 1: Time needed to accelerate from 80 to 120 for different gear ratios

4.3 Interpretation

It was noticed from the obtained results that the time required to accelerate from 80km/h to 120km/h is less at lower gear ratios. As the gear ratio increase, this time will also increase.
In order to understand the results, it is imperative to understand the meaning of short, normal and long gears . A "short gear" is a gear that gives excellent acceleration at the cost of cruising speed and efficiency, while a "long gear" gives a better cruising speed and fuel economy. The normal gear is an in-between solution for cars that should achieve decent acceleration as well as decent economy.
Consequently, it is quite expected that short gear ratios require less time. This is also coherent with what was obtained in the first experiment,where the value of the maximum acceleration was lower for higher gear ratios.
A good example that shows the difference of use for these gears is that trucks have very short 1st and 2nd gears in order to compensate for high cargo weight and be able to accelerate, while sport bikes tend to have tall lower gears in order to prevent or reduce wheelie tendency on hard acceleration .

5 Fuel Consumption at constant speed

In this section, fuel consumption of the engine for all the achievable gear ratios, has to be calculated at 3 different speeds:

- 50 km/h
- 90 km/h
- 120 km/h

5.1 Calculations

A Matlab code also was implemented to get the values of CO2 emissions and fuel consumption expressed in 1/100km. But, the gear ratios which are sufficient for the needed speed have to known. Taking into consideration the minimum and maximum values of motor speed.Then calculate the emissions and fuel consumption.The following points were considered :

- Calculating the total mass of the vehicle taking into account the inertia of the engine and the wheels
- Calculating the aerodynamics force ,friction force , and the force due to gravity caused by the change of slope (Using previously defined equations for those forces).
- Calculation the total resultant force of engine

  $$F = m_t.a - (F_{aero} + F_{friction} + F_{slope}) \tag{13}$$

  having a constant speed meaning the acceleration of the system is null.
- Calculating the torque due to the exerted forces :

  $$T_{eq} = F_{total} \times \frac{L_{ratio}}{120 \times \pi \times \eta_{GB}}(N.m) \tag{14}$$

- Calculating the power using the formula :

  $$POWER = 2$$

pi$\times RPM \frac{}{60 \times T_{eq}(15)}$

Calculating the break mean effective pressure (BMEP) usinf the formula :

$$BMEP = 0.126 \times \frac{T_{eq}}{Enginedisplacement}(bar) \tag{16}$$

using the value of BMEP we can interpolate the value of Break Specific Fuel Consumption having the data given in excel sheet .

Calculating the fuel consumption using the following formula :

$$FuelConsumption = \frac{BSFC}{\rho}(KW) \times \frac{100Km}{speed(km/h)} \times (\frac{L}{100Km}) \tag{17}$$

After getting the consumption in l/100Km the CO2 emissions according to the following chemical equation

$$CH_y + (1 + \frac{y}{4})O_2 \rightarrow CO2 + \frac{y}{2}H_2O \tag{18}$$

Then we do some calculations at stoichiometry

- 1 mole of diesel :1 mole of CO2
- i Liter of diesel : 820 grams of diesel
- 0.01671 liters of diesel : 44 g of carbondioxide

then we can get the expression of CO2 emissions to be :

$$CO2(g/Km) = \frac{44}{0.1371 \times 100}.Consumption(\frac{L}{100Km}) \tag{19}$$

	L1	L2	L3	L4	L5
50km/h	x	x	2.6053	1.92	1.85
90km/h	x	x	x	3.6109	3.1844
120km/h	x	x	x	x	4.4451

Table 2: Fuel consumption

	L1	L2	L3	L4	L5
50km/h	x	x	68.5949	50.55	48.723
90km/h	x	x	x	95.0793	83.849
120km/h	x	x	x	x	117.045

Table 3: CO2 emission

	L1	L2	L3	L4	L5
50km/h	x	x	2.6053	1.92	1.85
90km/h	x	x	x	3.6109	3.1844
120km/h	x	x	x	x	4.4451

Table 4: Fuel consumption empty mass

5.2 Results

After checking for each needed speed what are the sufficient gear ratios, then the following results in tables2,3 and 4 were obtained.

6 NEDC Fuel Consumption and CO2 Emission

This section will study the fuel consumption and CO2 emission in NEDC cycle.The New European Driving Cycle (NEDC) is a driving cycle designed to assess the emission levels of the car engine and fuel economy.It is composed of two parts: ECE (Urban Driving Cycle), repeated 4 times, is plotted from 0 s to 780 s; EUDC cycle is plotted from 780 s to 1180 s. The overall duration of the NEDC cycle is 1180 sec and the average velocity is 33.3161 Km/h.

6.1 ECE cycle

When the engine starts, the car pauses for 11 s, then slowly accelerates to 15 km/h in 4 s, cruises at constant speed for 8 s, brakes to a full stop in 5 s. At 49 s, the car slowly accelerates to 32 km/h in 12 s , cruises for 24 s, slowly brakes to a full stop in 11 s, then pauses for another 21 s . At 117 s, the car slowly accelerates to 50 km/h in 26 s, cruises for 12 s, decelerates to 35 km/h in 8 s, cruises for another 13 s, brakes to a full stop in 12 s, then pauses for 7 s . The cycle ends on 195 s after a theoretical distance of 994.03 meters, then it repeats four consecutive times. Total duration is 780 s (13 minutes) over a theoretical distance of 3976.1 meters, with an average speed of 18.35 km/h.

6.2 EUDC cycle

After a 20s stop the car slowly accelerates to 70km/h in 41s , cruises for 50s,decelerates to 50km/h in 8 s and cruises for 69 s, then slowly accelerates to 70 km/h in 13 s. At 201 s, the car cruises at 70 km/h for 50 s, then slowly accelerates to 100 km/h in 35 s and cruises for 30 s. Finally, at 316 s the car slowly accelerates to 120 km/h in 20 s, cruises for 10 s, then slowly brakes to a full stop in 34 s, and idles for another 20 s. Total duration is 400 s and theoretical distance is 6956 meters, with an average speed of 62.6 km/h.

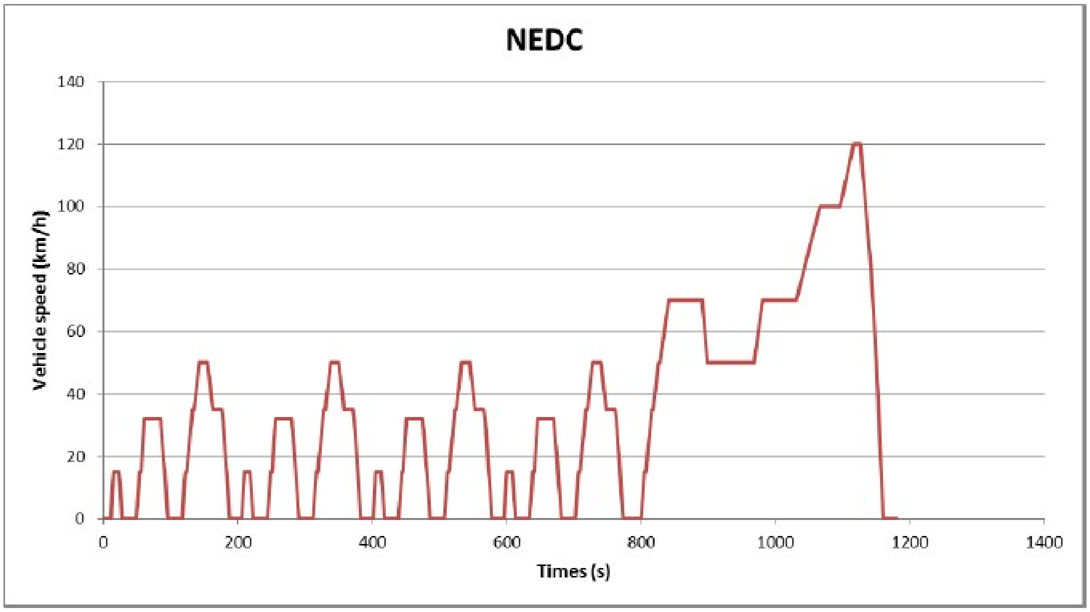


Figure 2: NEDC Complete Cycle

6.3 Calculation Methodology

6.3.1 Urban Driving Cycle ECE

The calculation was done following those steps :

1. Calculation of the instantaneous Velocity and the gear ratio each second from 0s to 195 s.
2. calculation of the RPM of the engine using the data calculated ,
   at this point man considerations must be taken , like if the gear is not coupled with the motor , the rotation speed will be 1250 rpm.
   If the car was at rest and starts to accelerate , then at this instant the clutch will be released and it would close completely when the rotational speed reaches 1250 rpm. And we must keep in mind that when we remain accelerating the engine speed is imposed by the gearbox.
3. Calculation of the forces after getting the RPMs, Gear ratios and Velocities.
4. Calculation of the torque and power.
5. Calculation of the Brake Mean Effective Pressure (BMEP)
6. Interpolation of the BMEP and RPM to get BSFC.
7. The calculation of the instantaneous fuel consumption with start stop system with all the other cases taking into consideration that consumption might null. The consumption at each point is calculated bu the summation of all the past instantaneous consumption values. The total consumptions (in grams) for the the whole urban driving cycle is calculated as follows:

$$UrbanFuelConsumption = \frac{Fuelconsumption_{15\%ECE} + 3 \times Fuelconsumption_{ECE}}{4} \tag{20}$$

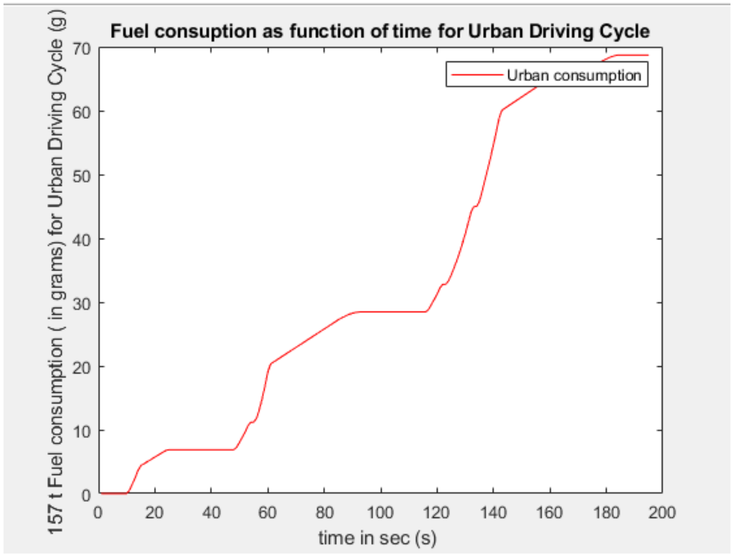


Figure 3: Cumulative Fuel Consumption for one ECE

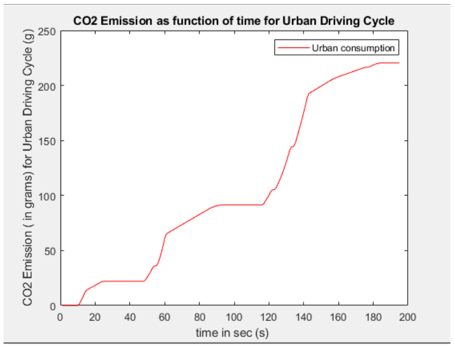


Figure 4: Cumulative CO2 emissions for one ECE

6.3.2 Extra Urban Driving Cycle EUDC

To calculate the fuel consumption, same steps are followed as for the ECE cycles but knowing that EUDC cycles are done on higher velocities and thus will require higher consumption rates.And same as before to get the instantaneous consumption at a certain instant we sum the previous consumption values.

6.3.3 For the New European Driving Cycle

The fuel consumption of the NEDC is calculated depending on Urban and Extra urban driving cycles , where for the UDC ,the consumption of ECE cycles are added to each other on the base of same temporal axis where 4 ECE cycles are followed by each other and then one EUDC cycle , Thus adding the consumption of this EUDC to the previously mentioned ECE cycles to obtain finally the consumption of NEDC .There is however an extra fuel consumption(20%) for the first urban driving cycle to take into account the catalyst and engine heat-up strategy.

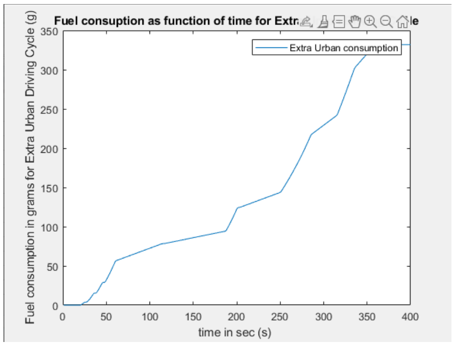


Figure 5: Cumulative Fuel Consumption for one EUDC

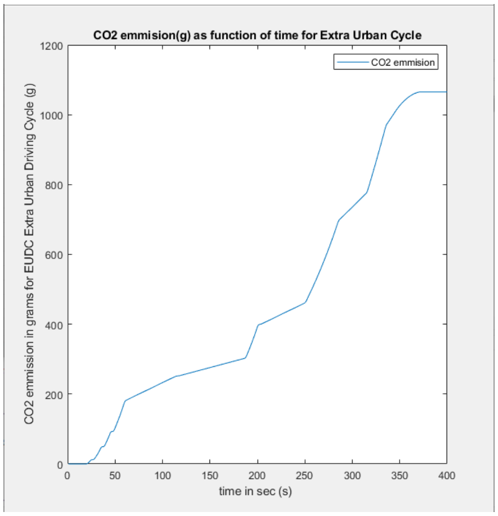


Figure 6: Cumulative CO2 emissions for one EUDC

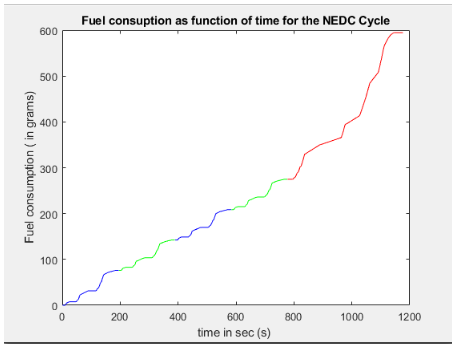


Figure 7: Cumulative Fuel Consumption for NEDC

6.4 Interpretation

From the previous graphs and tables for each urban , extra urban and overall cycle, it appears to be that the fuel consumption of Extra urban cycle is ore than that of urban cycle , that is due to the fact that the distance covered in EUDC is more than that covered in UDC meaning more consumed fuel.But for the average fuel consumption , it

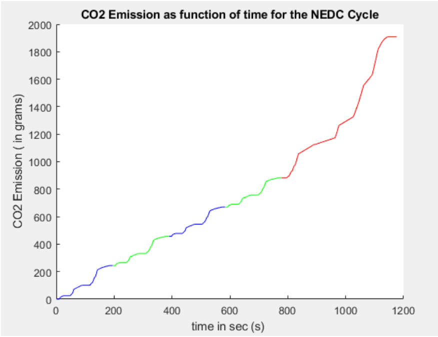
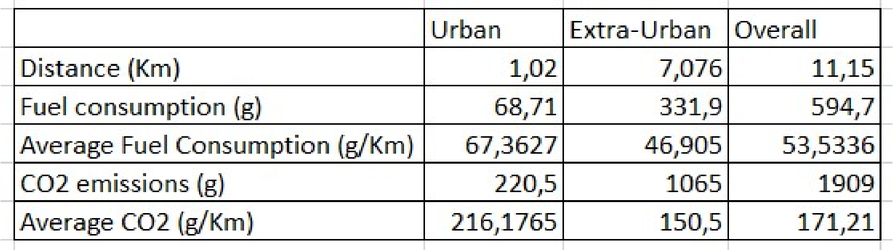


Figure 8: Cumulative CO2 consumption for NEDC



	Urban	Extra-Urban	Overall
Distance (Km)	1,02	7,076	11,15
Fuel consumption (g)	68,71	331,9	594,7
Average Fuel Consumption (g/Km)	67,3627	46,905	53,5336
CO2 emissions (g)	220,5	1065	1909
Average CO2 (g/Km)	216,1765	150,5	171,21

Figure 9: Results for Urban, Extra Urban, and overall cycles

seems to be higher for UDC that that for EUDC , that is justified by the nature of UDC , it is a cycle having higher acceleration zones that that of EUDC , and as what mentioned before , the fuel consumption increase with the increase of acceleration (the more acceleration zones in cycle ,the more fuel consumption) .Also it can be notices that inn EUDC the velocity is higher , meaning higher gear ratios , thus having lower fuel consumption (as mentioned before). For CO2 emissions ,it is shown in the graphs that the variation of those emissions has the same variation as the variation of the fuel consumption (as the shape of the curve) the more fuel is consumed , the more CO2 is emitted .This can be justified by the chemical relation between the reactants (fuel) and the Products (CO2) the more reactants , the more products we have .Hence the same results interpretation for the fuel consumption.

7 WLTP Fuel Consumption and CO2 Emission

This section aims to study the fuel consumption and CO2 emission of the WLTP cylce class 3b.The new WLTP procedure relies on the new driving cycles (WLTC – Worldwide harmonized Light-duty vehicles Test Cycles) to measure the mean fuel consumption, the CO2 emissions as well as the emissions of pollutants by passenger cars and light commercial vehicles.

The WLTP cycle is divided into 4 different sub-parts, each one with a different maximum speed:

1. Low, up to 56.5 km/h. Duration:589
2. Medium, up to 76.6 km/h. Duration:433
3. High, up to 97.4 km/h, Duration:455
4. Extra-high, up to 131.3 km/h, Duration:323

The distance covered by the WLTP is 23.266 km and a total duration of 1800(s).

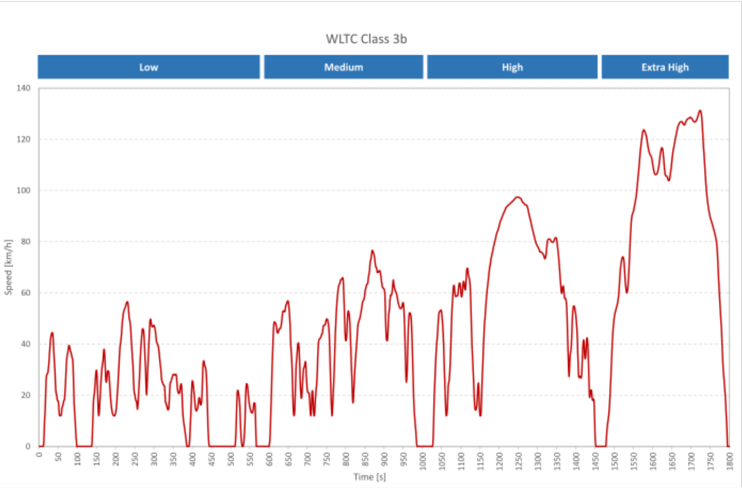


Figure 10: WLTP Cycle

7.1 Computation Methodology

The computation steps are the same as the NEDC cycle with some adjustments.

1. The constraints to be respected are:
   (a) When the car is not moving there is no gear engaged.The first gear is engaged two seconds before the car starts moving
   (b) Results must lie within consumption maps that are given.
   (c) Gear changes are performed in the same way as for the EUDC, this is also true for the clutch management when the car starts from 0 km/h
   (d) slope is null
2. This cycle differs from the NEDC in the choice of the gear ratio. In NEDC the ratio was given where as in this cycle the ratio must be chosen for optimal fuel efficiency and CO2 consumption. Generally, for low speeds(staring the car) and high motorway speeds(greater than 90 km/h), the first and fifth gears are the optimal choices, respectively.As a rule of thumb, for speeds below 30 km/h, second gear is used, and for 30-60 km/h and 60-90 km/h, the third and fourth gears are used, respectively.

   Using the function check, the maximum speeds of each phase are found to be within the given consumption map.

7.2 Interpretation

According to the obtained graphs and the table at the end, it can be seen that Fuel consumption and CO2 emission increase with each phase , so that they have their highest values at the extra high phase, but that is probably due to the distance covered rather than the higher speed. It is actually quite interesting to see that the high phase has the lowest fuel consumption and fuel efficiency and that was actually seen previously that higher gear ratios are more economic and as it was seen in the NEDC cycle. It is also seen that CO2 emission has the same behaviour as fuel consumption

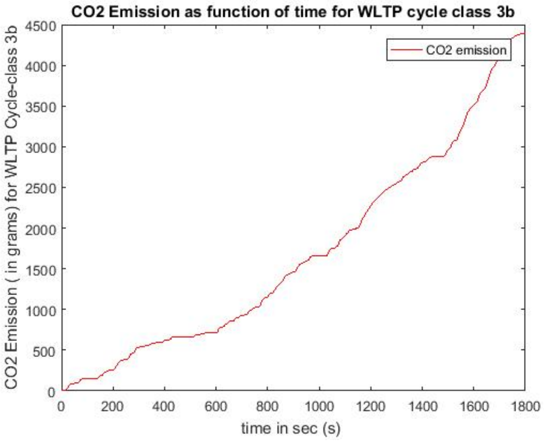


Figure 11: Fuel Consumption for WLTP

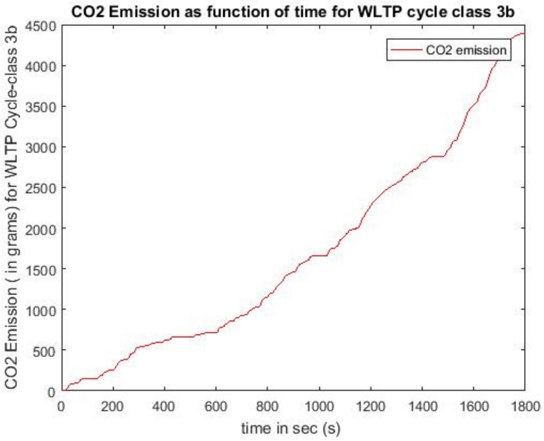
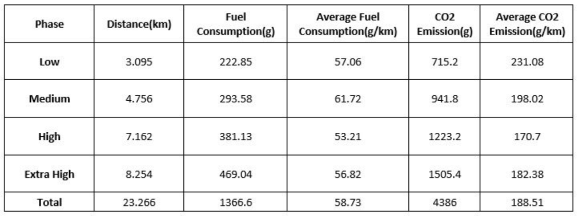


Figure 12: CO2 Emission for WLTP



Phase	Distance(km)	Fuel Consumption(g)	Average Fuel Consumption(g/km)	CO2 Emission(g)	Average CO2 Emission(g/km)
Low	3.095	222.85	57.06	715.2	231.08
Medium	4.756	293.58	61.72	941.8	198.02
High	7.162	381.13	53.21	1223.2	170.7
Extra High	8.254	469.04	56.82	1505.4	182.38
Total	23.266	1366.6	58.73	4386	188.51

Figure 13: Final Results of WLTP Cycle

which is in fact quite expected because they are related to each other by the combustion equation. More fuel means more CO2.

8 Comparison between NEDC and WLTP

The most noticeable difference is that the overall average values of fuel consumption and CO2 emission are higher in the WLTP cycle which is due to the greater distance of the WLTP cycle. , the cycle testing time will go up from 20 minutes for NEDC to 30 minutes for WLTP. Subsequently, the distance covered also takes a hike from 11 km to 23.25 km. Average speed also increases - from 34 km/h during NEDC testing to 46.5 km/h for WLTP tests. It can be seen that WLTP is the better cycle for the following reasons:

1. More realistic driving behaviour.
2. A greater range of driving situations (urban, suburban, main road, motorway)
3. Longer test distances
4. More dynamic and representative accelerations and decelerations
5. Higher average and maximum speeds

9 Conclusion

Piston engine is widely used in our world, it used in almost everything moving around us. An important parameter in it is its efficiency, which is also affected by many other parameters. These parameters and their effects are studied in this project, on a diesel engine.
This project helped us understand well the working principles of piston engine in general, specifically the diesel engine. Thanks to the course given by the professors, we were able to do this project.