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ANALYSIS OF THE INFLUENCE OF ENGINE'S AUXILIARIES SYSTEMS ON A PASSENGER VEHICLE LONGITUDINAL DYNAMICS.

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Abstract. *The increased restrictions on emissions regulations has made the automotive industry direct large resources to developing new hybrid and electric technologies, however less emphasis has been given to the influence of engine's auxiliary systems (Pumps, alternator, compressor) in the vehicle's dynamic and the total work produced. A complete direct-dynamic simulator for a passenger car was developed in MATLAB Simulink, where data referring to water pump, oil pump, alternator and air conditioner compressor was inserted. This vehicle was subjected to the New European Drive Cycle (NEDC), which is widely used in the automotive industry and has both urban and extra-urban phases. As a result consume of 26% and 59% of the total energy produced by the engine was consumed by the auxiliaries, urban cycle and extra-urban cycle respectively, while the air conditioner compressor and the alternator were responsible for consuming 16-40% and 5-12% of the engine's work respectively. Such results make explicit the major influence of these systems in the vehicle's total fuel consumption, mainly in the urban section of the test, and emphasize the importance of optimizing these systems in the engine's development.*

Keywords: *Simulation, Engine, Auxiliaries, Influence, Work*

1. INTRODUCTION

The increase on emissions restrictions impose by governments concerned with the environment and global warming has pressured the automotive industry to improve the efficiency of vehicle's engines. However, lately, vehicles have been achieving levels of emissions that are very close to zero.

This, combined with the future shortage on fossil derived fuels, presents a huge challenge for the industry.

Nowadays one of the biggest penalties of the powertrain efficiency for combustion engine vehicles is the load derived from several auxiliaries attached to it. Although indispensable for the good operation and comfort of the vehicle, actuators, such as, the water pump, the oil pump, alternator and air conditioner compressor, require considerable amounts of energy without contributing directly to the vehicle's motion.

This project has the objective of analyze, the impact of these auxiliaries systems on the longitudinal dynamic of a passenger car, by focusing on the New European Drive Cycle (NEDC). This cycle is of particular interest because it combines regions of urban testing and extra-urban testing.

In order to accomplish this task a direct dynamic simulator was developed in the MatLab Simulink software. In this simulator were included the loads of the water pump, oil pump, alternator and air conditioner compressor, which were scaled according to data found in the literature.

2. DEVELOPMENT OF THE SIMULATOR

Equation 1 states Newton's second law for the longitudinal forces on a passenger vehicle.

$$F_{engine} - F_{brakes} - D_a - R_x - F_{slope} = (m+m_I)a \qquad (1)$$

Where,
F_{engine} = Force developed by the engine with auxiliaries
F_{brakes} = Force developed by the brakes
D_a = Aerodynamic drag force
R_x = Rolling resistance force
F_{slope} = Force from the road inclination
m = mass
m_I = inertial mass
a = acceleration

Combining these forces in the Simulink environment the vehicle's base simulator was build (figure 1).

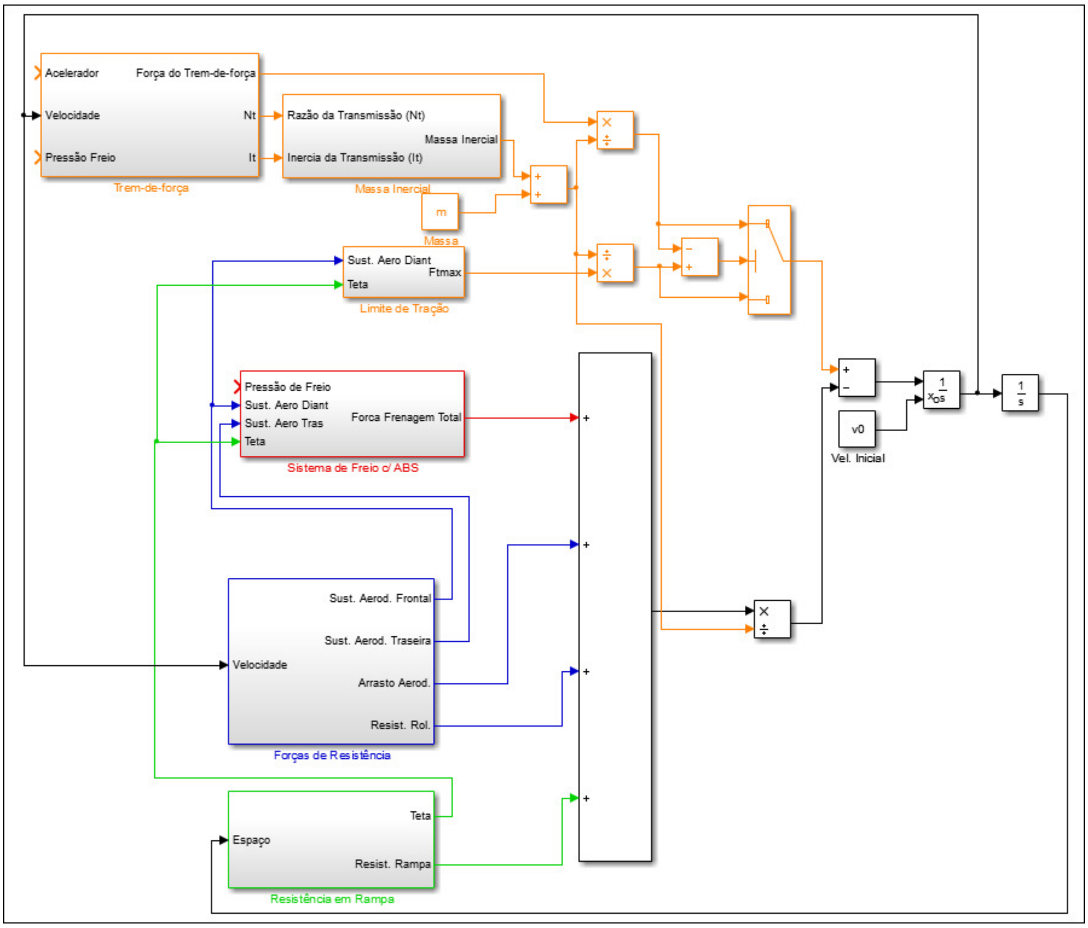

Figure 1. Vehicle's Simulator on MatLab Simulink

The brake force, simulated in red in Fig. 1, was build using equation 2.

$$F_{brakes} = 2 \text{ x } G_f \text{ x } P_f/r + 2 \text{ x } G_r \text{ x } P_r/r \qquad (2)$$

Where,
Gf = Front brakes gain
Pf = Front brakes pressure
r = wheel's dynamic radius
Gr = Rear brakes gain
Pr = Rear brakes pressure

In this equation, the braking system individual parts were simplified in one gain.

Both resistance forces, aerodynamic and rolling, are represented on the blue portion of the simulator. These forces were simulated according to Eq. 3 and 4 respectively.

$$D_a = 0.5 \text{ x } \rho \text{ x } V^2 \text{ x } C_d \text{ x } A \qquad (3)$$

$$R_x = f_r \text{ x } W \qquad (4)$$

Where,
ρ = air density
V = vehicle velocity
C_d = Aerodynamic Air coefficient
A = Vehicle's frontal area
f_r = rolling coefficient

The force derived from road inclination, in green on Fig. 1, was not used in this simulation, due to the driving cycle being developed on plane roads.

2.1 Powertrain force

The simulation of the powertrain force, orange in Fig. 1, required more focus, since it houses the auxiliaries load. Equation 5 shows the mathematical base of the powertrain force.

$$F_{powertrain} = F_{engine} - F_{Ilosses} = (T_e - T_{aux}) \times N_{tf} \times \eta_{tf}/r - F_{Ilosses} \quad (5)$$

Where,
$F_{powertrain}$ = Powertrain full force
$F_{Ilosses}$ = Inetial losses (These are simplified on the inertial mass of eq. 1)
T_e = Engine Torque
T_{aux} = Auxiliaries Torque
N_{tf} = Transmission ratio from engine to wheels
η_{tf} = Transmission efficiency

The expanded engine force simulator can be seen on Fig. 2.

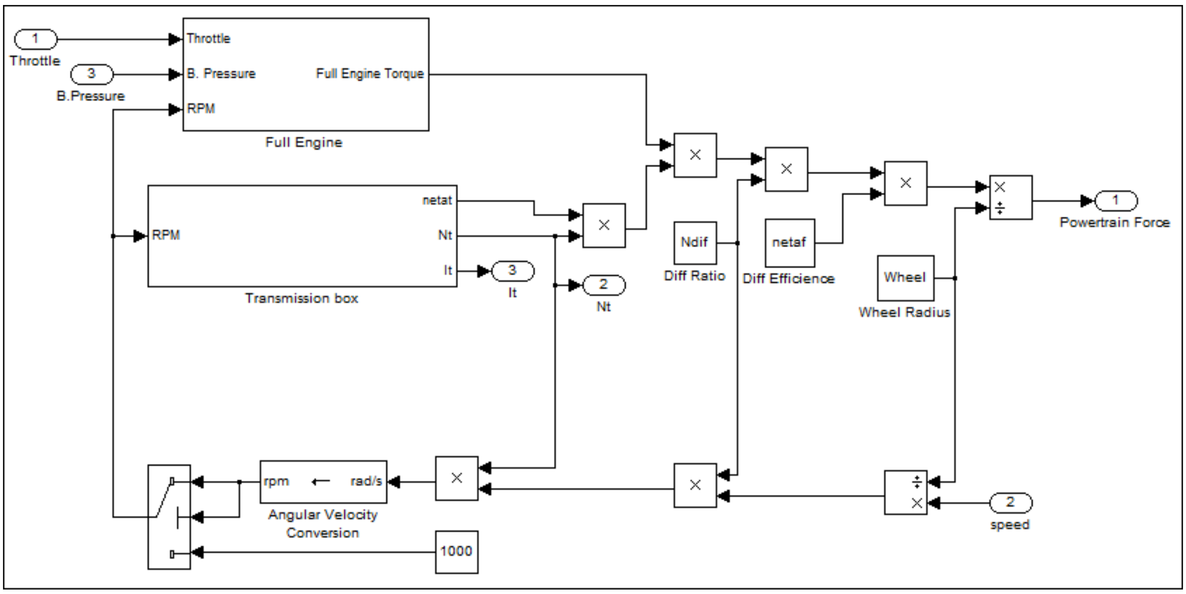

Figure 2. Engine Force Simulator

Expanding on the "Full Engine" block, Fig. 3, the simulator of the mapped engine and the auxiliaries is displayed. These subsystems are governed by a idling control that allows for the auxiliaries to contribute with the braking system when the vehicle is coasting, and the engine to sustain the auxiliaries load during stops and low speeds.

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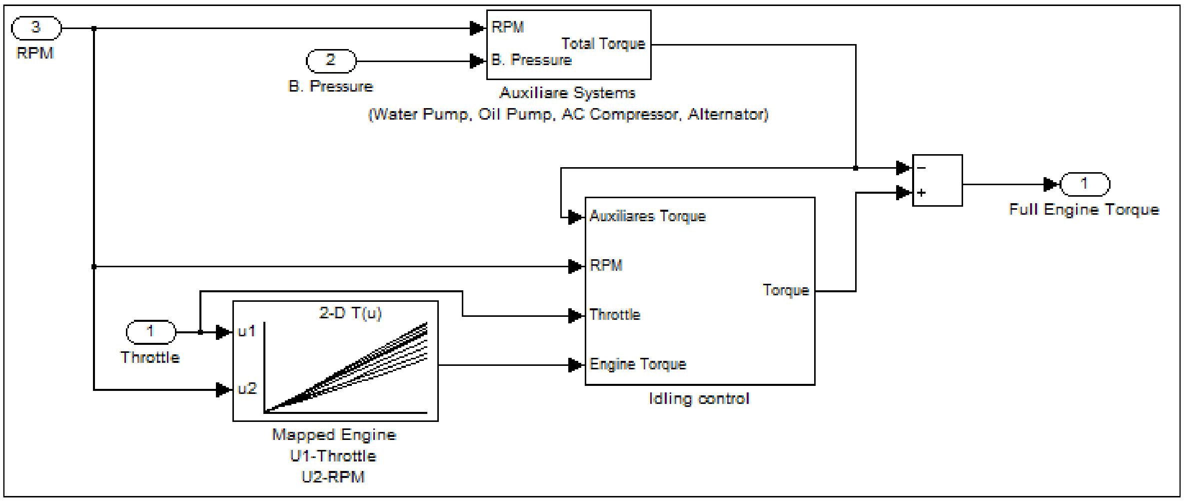

Figure 3. Full Engine Block

2.1.1. Water pump load sizing

The water pump was sized from the study of cavitation on a 2.0 gasoline engine's water pump (Kim, Hwang, Lee, & Lee, 2008). In this study, a torque x engine speed was draw, and by considering the cycle done under engine's steady state temperature, 90ºC, the water pump load could be sized (Fig. 4).

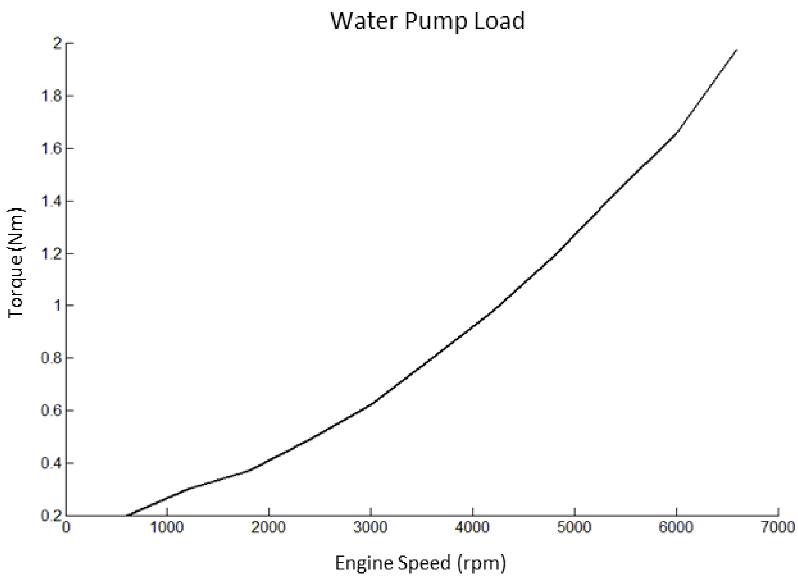

Figure 4. Water Pump load (Kim, Hwang, Lee, & Lee, 2008)

2.1.2. Oil Pump load sizing

The lack of papers on modern engine's oil pumps posed a bigger difficulty on sizing this system. So, to reach this objective two graphics were used. Figure 5 relates the oil system pressure with the engine's speed, whereas, fig. 6 (Inaguma, 2011), relates the system pressure, and the pump's speed, with its load.

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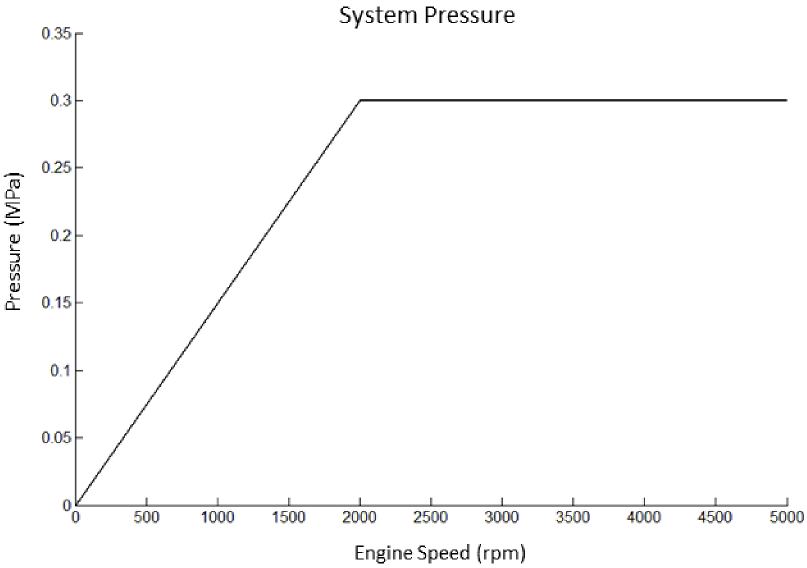

Figure 5. Oil system pressure x engine speed

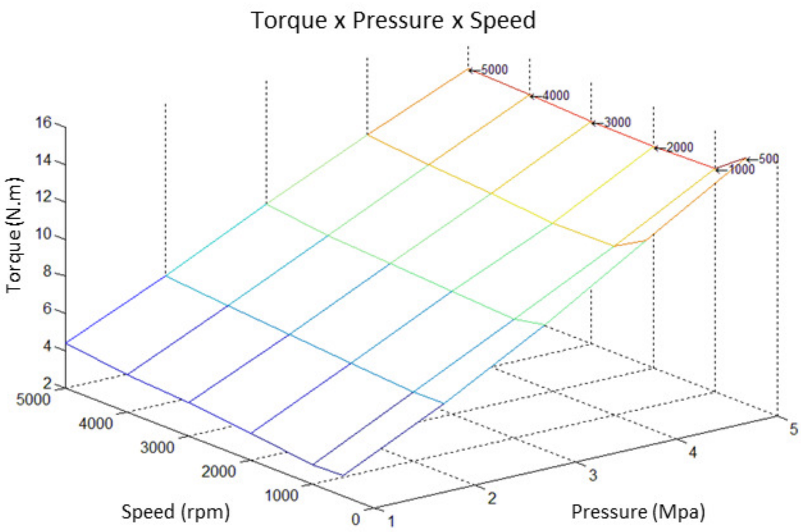

Figure 6. oil pump Load x system pressure x oil pump speed

2.1.3. Alternator load sizing

The alternator load was sized according to the SAE J1343 norm. It uses eq. 6 with table 1 to estimate the electric power needed and thus the alternator load.

$$T_{alt} = I_{cons} \text{ x } V_{sist}/(\omega_{eng} \text{ x } \eta_{belt}) \quad (6)$$

Where,
T_{alt} = alternator torque
I_{cons} = total electrical current needed for the electric system
V_{sist} = electric system voltage
ω_{eng} = engines speed
η_{belt} = belt efficiency

The voltage utilized for the electric system was 12V.

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Table 1. Electrical consumers required current. (SAE J1343)

Consumer	**Current [A]**	**Duty Cycle**
Brake Light	4.3	Whenever brake system is utilized
Radio	4.4	On (100%)
Frontal Light	10	On (100%)
Back Light	1.2	On (100%)
Panel Lights	1	On (100%)
Air Conditioner Fan	65	On (50%)
Fuel Pump	2.6	On (100%)
Panel Indicators	1	On (100%)
Engine cooling fan	70	On (7%)

2.1.4. Air conditioner compressor sizing

The SAE J1343 was also used in order to size the air conditioner compressor. According to the norm, the system's load should be sized using its full power with a duty cycle coefficient. To cycles predominately urban the duty cycle used is 0.5.

Equation 7 show the formula used to find the compressor torque.

$$T_{compr} = P_{max} \text{ x } C_{cycle}/\omega_{motor} \quad (7)$$

Where
T_{compr} = compressor torque
P_{max} = maximum compressor power
C_{cycle} = duty cycle coefficient

The maximum compressor power adopted was 4.5kW.

2.1.5. Auxiliaries Simulator

Figure 7 shows the auxiliaries loads build in the Simulink environment.

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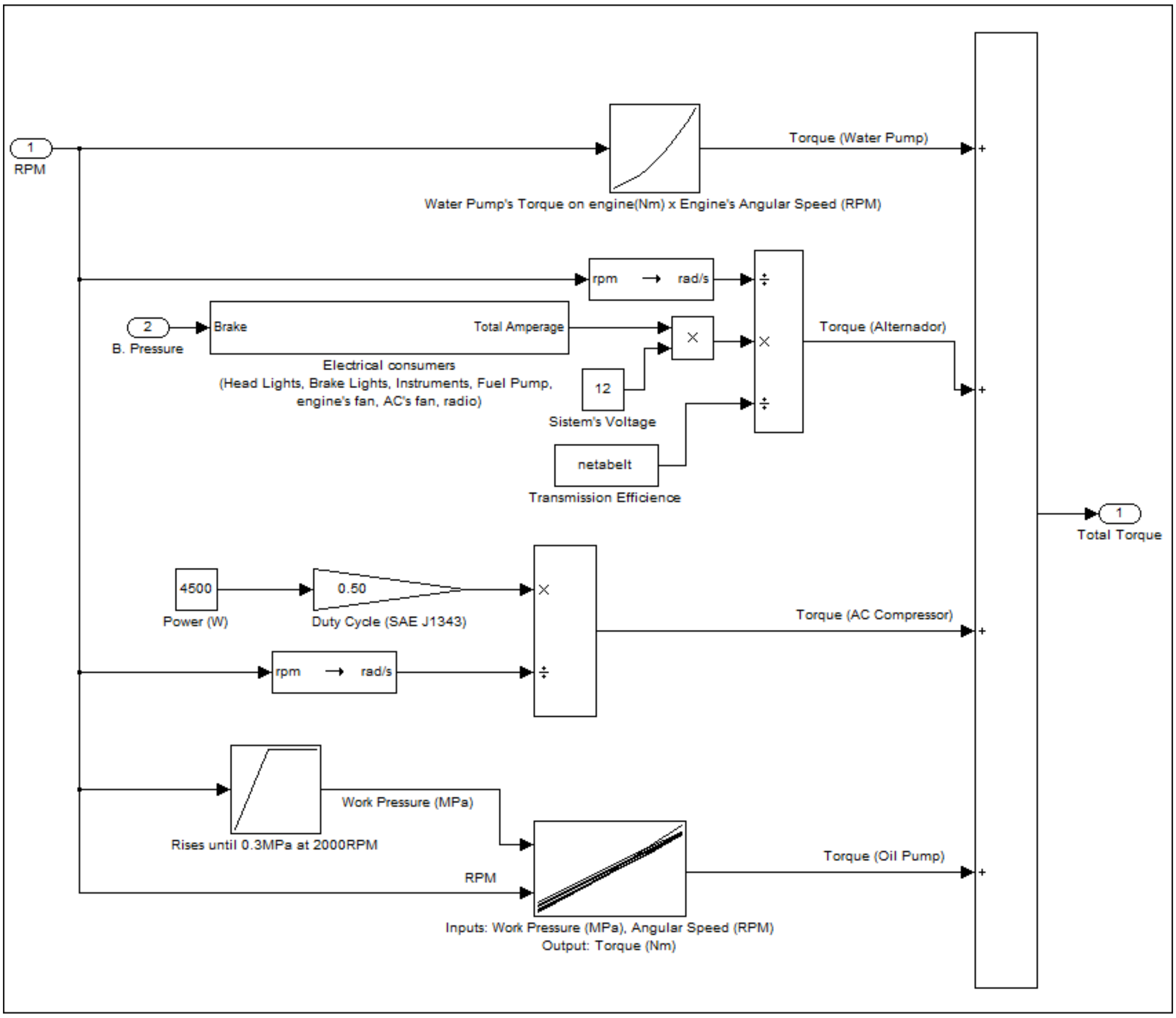

Figure 7. Auxiliaries loads simulator

2.2. NEDC vehicle control

To control the vehicle dynamics through the NEDC (Fig. 8) a controller was used, but because the system presented a second-degree dynamic behavior, an integral controller had to be combined with a proportional-integral-derivate controller (Fig. 9) in order to avoid a steady-state error.

The NEDC was selected because it is formed by four instances of low velocity, urban cycle, that lasts 780s and then it is completed by one instance of high velocity, extra-urban cycle, that lasts 400s.

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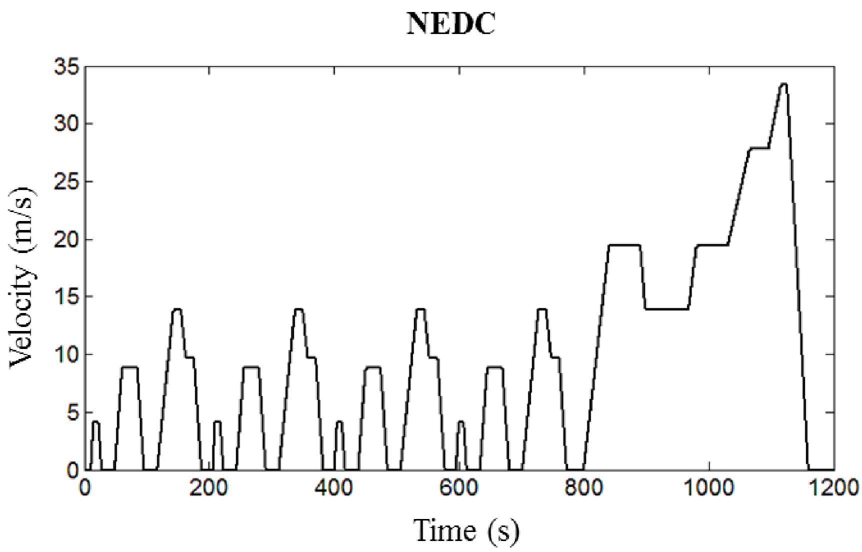

Figure 8. New European Drive Cycle

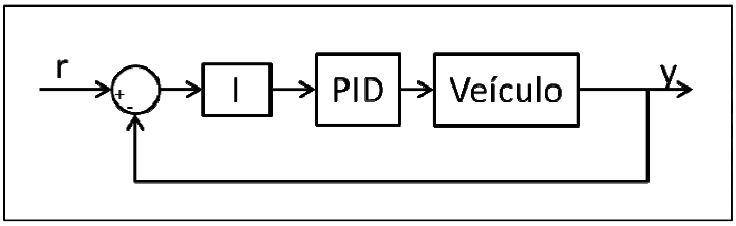

Figure 9. Block diagram of vehicle controllers

In order to allow for a good settling time and reduced overshoot the gains used in the controller are described in table 2.

Table 2. Gain used on controller

Integral (I)	Proportional (PID)	Integral (PID)	Derivative (PID)
50	500	1	375

Figure 10 shows the controller (in cyan) integrated with the vehicle's simulator.

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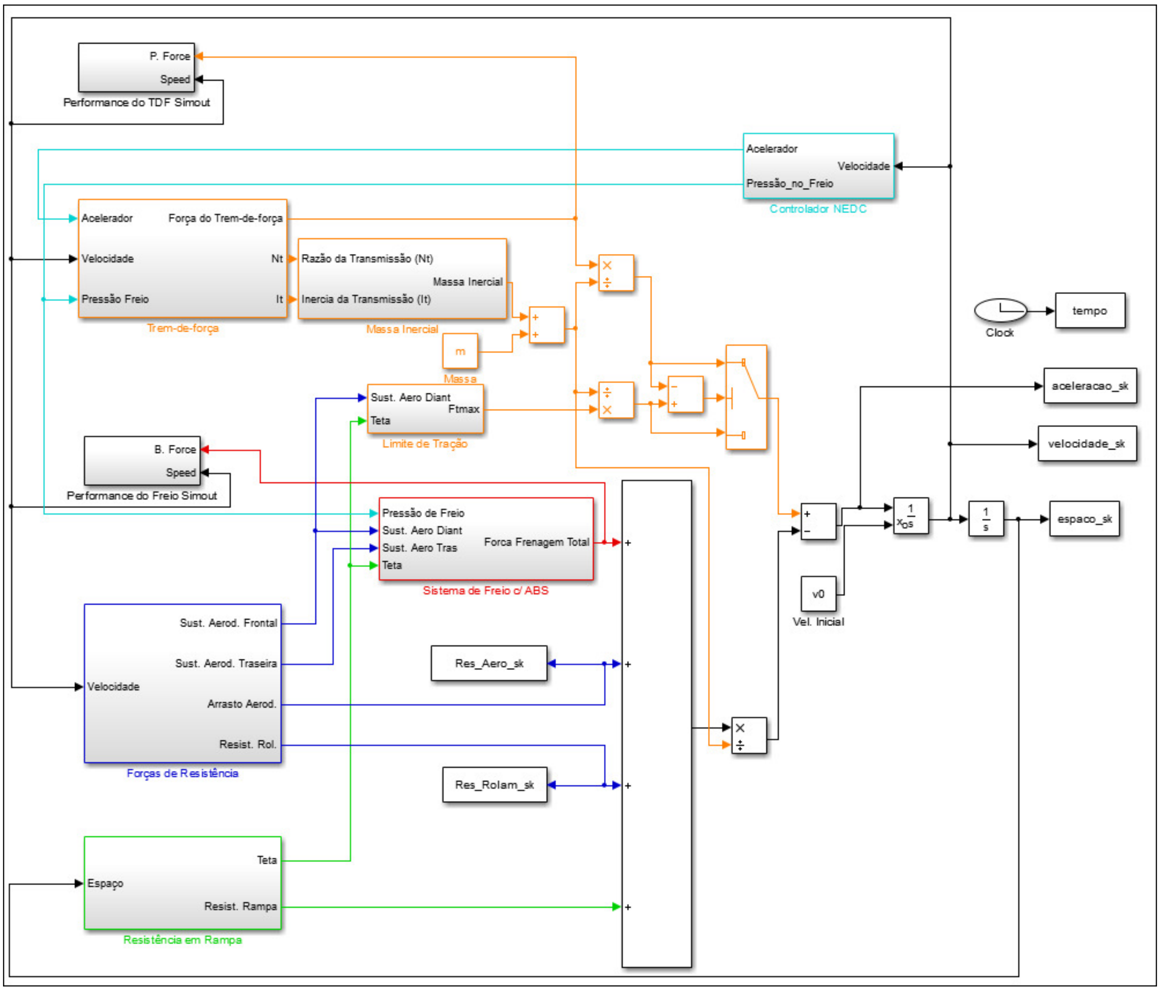

Figure 10. Vehicle simulator with controller

3. RESULTS

By analyzing the interactions between the engine torque and the auxiliaries torque (Fig. 11), it is possible to see that during the acceleration instances of the cycle, the engine keeps an elevated driving torque. This torque decreases during instances of constant velocity and reaches zero when the vehicle starts to brake. This occurs because the engine is saving fuel during this initial coasting, until it reaches the idling control velocity. From this velocity down and during the stationary portions of the cycle, the engine provides the amount of torque equal to which is been requested by the auxiliaries.

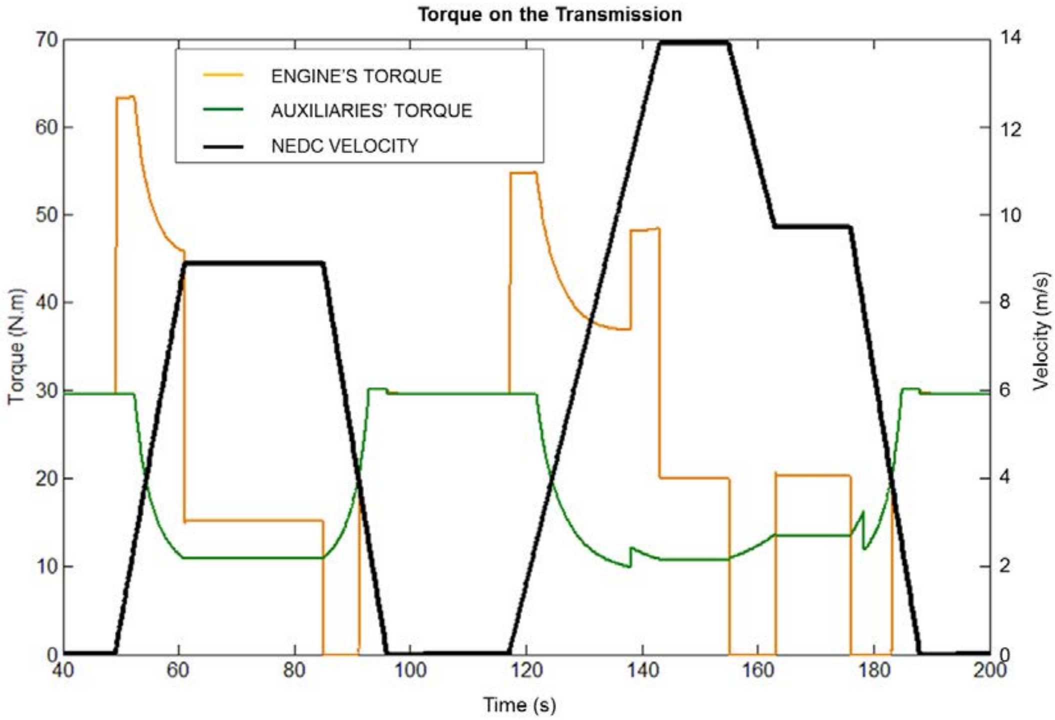

Figure 11. Torque on the vehicle transmission

Finally, looking at the work performed by the auxiliaries, the engine and braking system it was possible to build tables 3 and 4.

Table 3. Work on NEDC Urban cycle

	NEDC Urban (0s-780s, 4067m)			
System	**Work (MJ)**	**% from engine**	**Work (MJ)**	**% from braking**
Compressor	1,589	40,0%	0,201	27,20%
Alternator	0,491	12,3%	0,066	8,93%
Oil Pump	0,205	5,2%	0,037	5,01%
Water Pump	0,080	2,0%	0,013	1,76%
Total	2,365	59,5%	0,317	42,90%
Engine	3,977	100		
Full Braking			0,739	100

Table 4. Work on NEDC Extra-Urban Cycle

	NEDC Extra-Urban (780s-1180s, 6956m)			
System	**Work (MJ)**	**% from engine**	**Work (MJ)**	**% from braking**
Compressor	0,831	16,5%	0,087	16,38%
Alternator	0,255	5,1%	0,029	5,46%
Oil Pump	0,189	3,8%	0,018	3,39%
Water Pump	0,075	1,5%	0,007	1,32%
Total	1,350	26,8%	0,141	26,55%
Engine	5,036	100		
Full Braking			0,531	100

By analyzing these two tables, it is possible to perceive the difference between the amount of energy spent on the urban cycle, almost 60% of the total produced at the engine, and the extra-urban cycle, around 27%. It is also possible to verify that the air conditioner compressor accounts for most of the energy lost on auxiliaries, 40% on urban cycle and 16.5% on the extra-urban.

These numbers bring forward the necessity of improving these systems efficiency in order to improve the full engine efficiency. Mainly, when we consider that the air conditioner compressor uses a clutch to disperse energy on part-load instances, a method highly inefficient.

Another part that can't be ignored is the amount of braking energy these auxiliaries absorb, 42.9% on the urban part and 26.55% on the extra-urban part, helping the braking system stop the vehicle.

3. CONCLUSION

With the results obtained by this simulation a clear map of which systems should be focused on in order to optimize the engine's energy use is drawn. Focusing on the air conditioner compressor can produce great results, since it is responsible for consuming huge amounts of energy from the engine, and is nowadays controlled by a highly inefficient method.

An in-depth study of the alternator is necessary to provide better understanding of its loads, since it represents all the electrical systems of the vehicle. The use of more efficient lamps and electrical fans can present a good way to reduce this system load on the engine.

As for the oil and water pump, off-engine electrical pumps have been studied and proved to present better results than the engine dependent ones, since they can be controlled focusing on the engine's temperature and not as a function of engine speed.

It is also important to point out that with fuel cut-out strategies the energy normally wasted on the braking system can be used to sustain the auxiliaries, showing good savings on brake wear.

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

7. APPENDIX

Table A1. Reference values used in the vehicle's simulation

Frontal Area	2,552 m
Transmission Efficiency	0,99
Wheel Radius	0,3048 m
Frontal Brake Gain	1,469 N.m/psi
Rear Brake Gain	1,017 N.m/psi
Grad Coefficient	0,358
Mass	1200 kg
Belt Efficiency	0,98