OPTIMIZATION OF THE UPPER LIMIT ENGINE SPEED IN URBAN BUSES USING GENETIC ALGORITHM TECHNIQUE

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Abstract. *The upper limit engine speed for each gear, for urban buses, is defined through drivers' experiences and instructors without the required technical considerations. Many parameters might affect fuel consumption in urban buses, and determine an equation that relates them with the upper limit engine speed for each gear might allow its optimizaticobon and minimize fuel consumption. The present study will consider mathematical models obtained in the literature in order to determine a model that relates those different operational parameters and fuel consumption in urban buses. Using the genetic algorithm technique, the optimum equation for the problem will be determined and the optimization of the maximum engine speed for each gear obtained, minimizing fuel consumption.*

The possibility of improving urban buses' operating companies is the essential motivation in this study. The presented relation, between the upper limit engine speed for each gear and fuel consumption, can be optimized leading to minimization of the latter. Improvements in those aspects would reduce costs in vehicle maintenance, penalties related to improper conduction, increase passengers' comfort and boost the company's image.

Keywords: *Automotive Powertrains, Fuel Consumption, Constrained Parameter, Evolutionary Algorithms*

1. INTRODUCTION

The upper limit engine speed for each gear is currently indicated by the manufacturer and, when necessary, defined through experimental tests by bus companies. The test consists in experimenting different limits of the engine speed in each gear, for the line rated as the most challenging one, until the bus obtains the minimum fuel consumption while still completing it. The method results in a maximum engine speed for each gear that is the closest one to the minimum fuel consumption for this specific line. However, the method disregard the diversity of lines operated by buses, as for any other line the maximum upper limit engine speed for each gear is adjusted for a performance higher than needed, leading to fuel consumption surpluses. Those experiments are poorly documented and don't follow a methodology that reassures reliable results.

The study aims to, through the presented context, optimize the maximum upper limit for each gear of urban buses considering lines, or group of lines, characteristics' and consequently minimizing its fuel consumption.

By the means of establishing the relation between the maximum upper limit speed for each gear and fuel consumption, for the considered conditions, it's possible to optimize those limits and obtain the speeds resulting in the minimum fuel consumption. This relation will be obtained through equations in the literature and in national and international norms, being then inserted in the optimization program that will deliver the expected results using the genetic algorithm technique. The line discussed may be acquired by statistical data, practical experiments and norms.

The presented study will be capable to produce a simple relation between the maximum upper limit engine speed for each of the 6 gears of a urban bus.

2. THE UPPER LIMIT ENGINE SPEED AND FUEL CONSUMPTION

All following calculations were made considering the OF-519 MBZ bus and data was obtained in the manufacturer website address. The fuel consumption simulation was based on the *United States Environmental Protection Agency* denominated as *EPA Urban Dynamometer Driving Schedule (UDDS)*.

2.1. POWERTRAIN

Engine data may be obtained from the manufacturer website by the performance information as shown in Fig. 1.

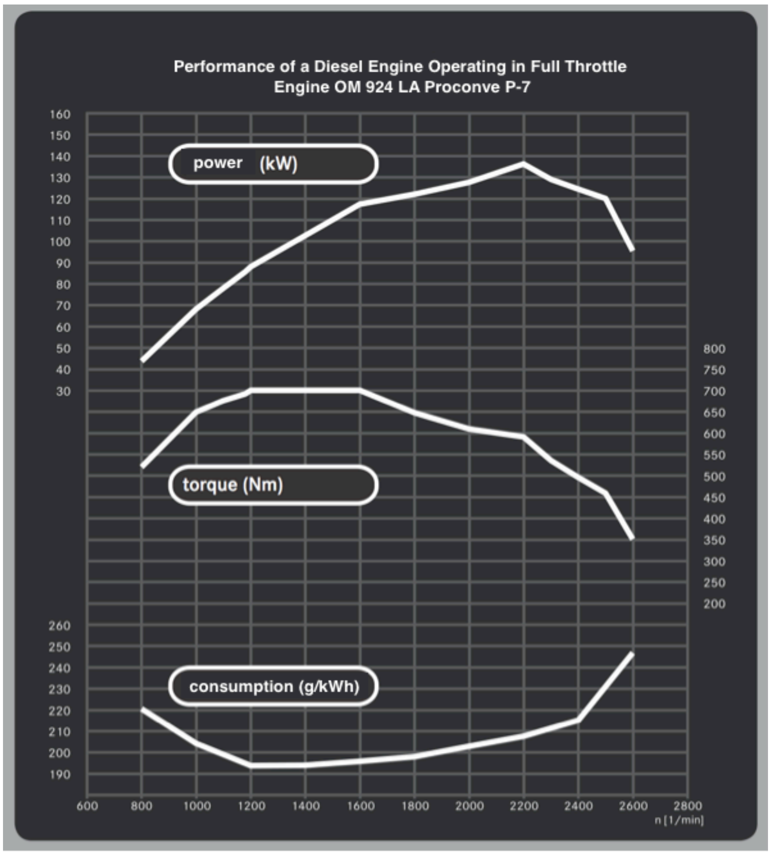

Figure 1 Typical Performance of a Diesel Engine Operating in Full Throttle (manufacturer website)

The Brake Power (BP) is a measure of the power available from the engine crankshaft to do work, such as moving the vehicle down the roadway and the Brake Specific Fuel Consumption (BSFC) is inversely proportional to the efficiency as a lower value indicates higher engine efficiency (Hoff & Gregory, 2003).BSFC in not the same thing as fuel economy and is defined as a ratio of fuel used to power produced. These two components are sufficient for the consequent fuel simulation test.

Through the driveline equations and the kinematics of the wheel, the speed of the vehicle and the speed of the engine can be related. According to Hoff & Gregory (2003) this derivation is simply shown as Eq. (1).

$$R_v = \frac{n}{v} = \{\frac{R_a * R_t * 2660}{r_r}\} \quad (1)$$

Where R_a is the Axle Ratio, R_t is the Transmission Ratio for each gear, r_r is the Average Effective Rolling Radius of the tire in *mm*, N is the Engine speed in *rpm* and V is the Vehicle speed in *km/h*.

2.2. ROAD LOADS

The road loads applied to an urban bus are shown in Fig. 2. The loads presented will be compared with different buses configurations, which need to necessarily produce sufficient power in overcoming it. As the same kind of bus is being compared, the road loads may be thought as a constant obstacle to the vehicle that the different configurations of upper limit speed in each engine will lead to different fuel consumptions.

In case, throughout the simulation, a vehicle is unable to overcome the sum of road loads it is automatically discarded.

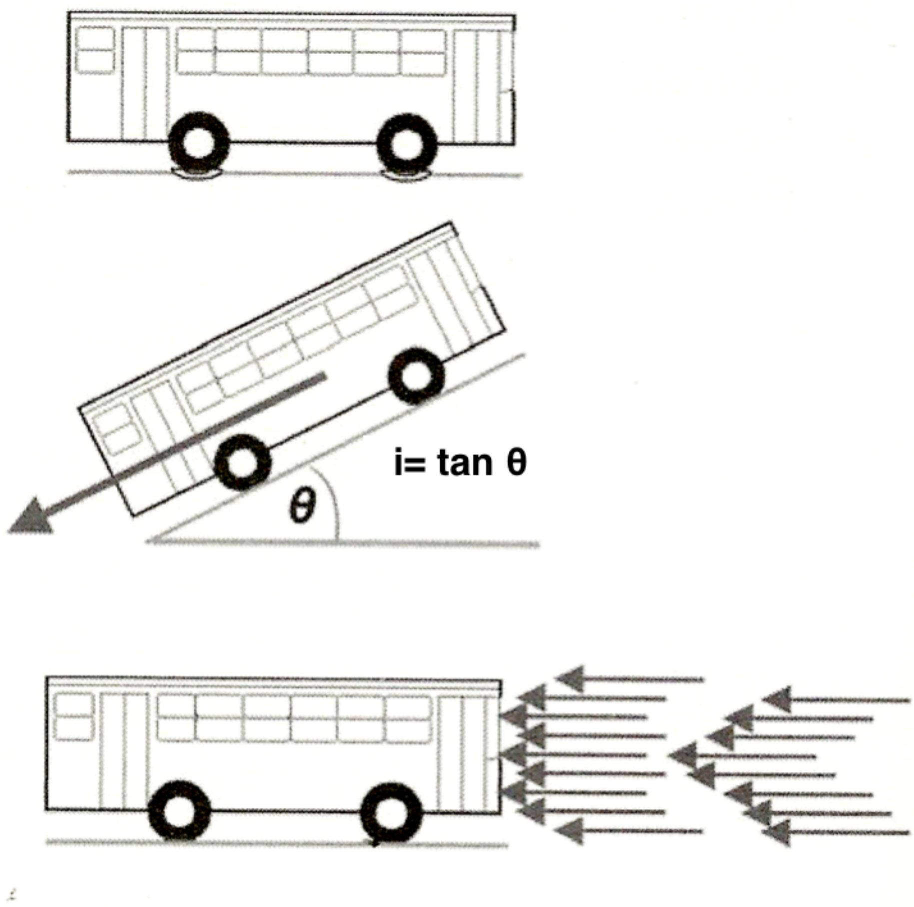

Figure 2 Road loads for a moving bus (Monteverde, 2012)

Rolling Resistance (FR_{ROL}) can be calculated by Eq. (2).

$$FR_{ROL} = R_{ROL} * PBT \quad (2)$$

Where R_{ROL} is the Rolling Resistance Coefficient, and PBT is the Vehicle weight.

Inclination loads (FR_{INC}) can be calculated by Eq. (3)

$$FR_{INC} = i * PBT \quad (3)$$

Where i is the $\tan\theta$, and represents the height gained for each 100 meters covered.

Aerodynamic loads (FR_{AR}) can be calculated by Eq. (4)

$$FR_{AR} = \frac{C_a * A_f * v^2}{212} \tag{4}$$

Where C_a is the Aerodynamic Coefficient, and A_f the Frontal Area.

Inertia Loads (F_p) can be calculated by Eq. (5).

$$F_p = \frac{PBT}{g} * a \tag{5}$$

Where g is the Gravitational Acceleration, and a the Acceleration Demanded.

2.3. THE OPTIMUM UPPER LIMIT ENGINE SPEED AND FUEL CONSUMPTION

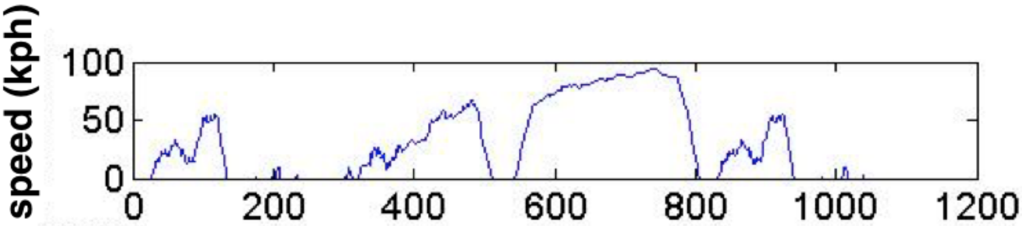

Figure 3 Data for Vehicle Speed During the Test

The optimum upper limit engine speed will be determined by simulating the vehicle in the course presented in Fig. 3 and may be obtained in the Environmental Protection Agency (EPA) website. Through the simulation it is possible to calculate the fuel economy, and by testing different values for the upper limit engine speed in each gear reach the desired optimum.

Fuel economy (ec) is given by Eq. (6).

$$ec = \frac{S_n}{V_f} \tag{6}$$

Where S_n is the Distance, and V_f the Volume of Diesel.

V_f, in the other hand, is given by Eq. (7)

$$V_f = \frac{m_{ft}}{\rho_f} \tag{7}$$

Where m_{ft} is the Total Mass, and ρ_f the Fuel Density.

m_{ft} is then given by Eq. (8).

$$m_{f(i)} = dm_{comb}(i) * (t_i - t_{i-1}) \tag{8}$$

Where dm_{comb} is the Fuel Flow and t equals Time.

Lastly dm_{comb} can be obtained by Eq. (9)

$$dm_{comb}(i) = BP(i) * BSFC(i) \tag{9}$$

Figure 3 presents the velocity that each bus, with a different configuration, will be simulated. For each data in Fig. 3 in a specific gear will result in a different engine speed, which will then point out to a different Fuel Flow.

As the simulation is done with the same vehicle, only with different upper limits for the engine speeds, notice that this is the only variable in the simulation and will be crucial for minimizing fuel consumption.

3. THE OPTIMIZATION ALGORYTHM

The coding for the optimization is based on a brother project from Universidade de Brasilia (UnB) from Colherinhas & Dias (2014) and follows a standard flowchart of a genetic algorithm-based optimization process, as shown in Fig. 4.

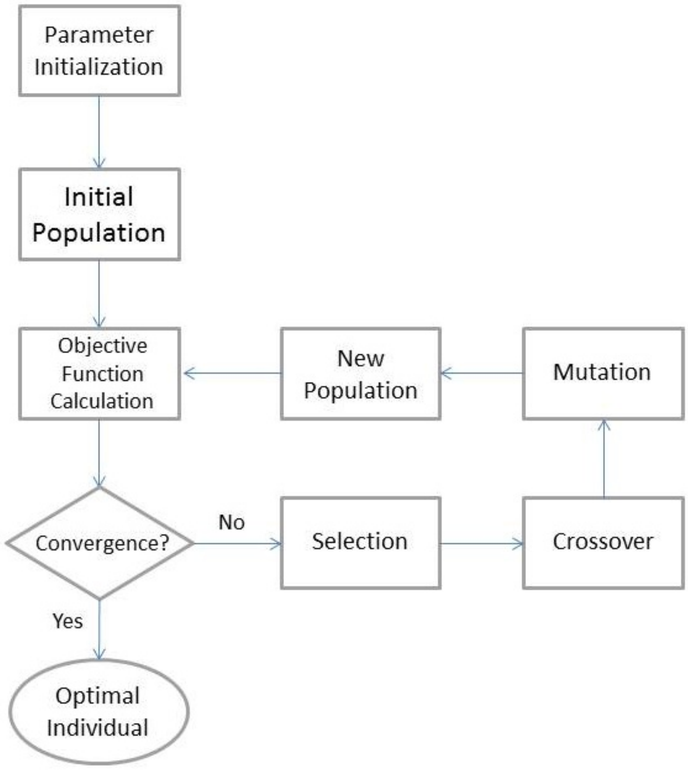

Figure 4 Optimization Flowchart

The initial population of 150 individuals is created by generating random positions in a vector consisting of values of engine speed going from 1000 to 2800 at a 50 *rpm* step value. The first value was selected in order to prevent the engine from going below the rotation in which it shuts itself down (800 *rpm*), while the latter was chosen so that it stays clear from the tachometer's "red-zone", the engine speed values in which the structural integrity of the engine might be compromised.

Afterwards, each individual goes through its objective function (OF) calculation, which means having the bus reach the target speeds shown previously in Fig. 3 and calculating its fuel consumption during its course and showing it in kilometers per liter (*km/L*). Additionally, the brake power (*BP*) created from the resistive forces acting on the bus is also calculated and compared to the brake power provided by the engine. If the resistive brake power (or required brake power, BPreq) is, at any point during which the bus is trying to move, higher than the brake power from the engine, the individual is considered to have failed its mission and suffers a high penalty in its OF value. In this way the failed individuals have their chances of reproduction lowered during the selection stage later in the algorithm, but do not have their genes completely removed from the gene pool.

The third stage is the selection, which uses the roulette method to select which individuals will reproduce to create the next generation. This means that individuals with a high OF value will be more likely to be selected, while individuals that are either "less adapted" or simply failed will have a lower chance (Mognon, 2014).

Next come the genetic operators, crossover and mutation, which happen simultaneously. The crossover stage picks two parents from the parent list created during the previous stage and mixes their genes (engine speeds) using a randomly created percentage to create two new individuals for the next generation. If, during this stage, a second randomly generated percentage takes on a value lower than 7% (Sirinvas & Patnaik, 1994), a mutation protocol is activated, in which the engine speeds of the newly spawned individuals are modified up to 5% higher or lower than their original value. After this stage, the new population of 150 individuals is created, forming the second generation, and put through its OF calculation. The algorithm ends after 250 generations go through the OF calculation stage. Afterwards, it is compared to the total fuel consumption of a bus changing gears at a constant engine speed value.

The genetic algorithm code ran and was developed on Matlab 2011a, on the Windows 7 operating system. It has a total running time of 9 minutes and 32 seconds.

4. RESULTS AND ANALYSIS

The bus type selected for results and analysis was the Mercedes-Benz OF 1590, with the considerations shown in Table 1.

Table 1: Considerations for OF 1590

OF 1590		
Vehicle Weight	PBT	15 t
Rolling Resistance Coefficient	R_{rol}	0,011
Frontal Area	A_f	8,3 m^2
Aerodynamic Coefficient	C_a	0,65
Equivalent to $tan\theta$	i*	2,6%
Transmission Ratio 1	R_{t1}	9,201
Transmission Ratio 2	R_{t2}	5,230
Transmission Ratio 3	R_{t3}	3,145
Transmission Ratio 4	R_{t4}	2,034
Transmission Ratio 5	R_{t5}	1,374
Transmission Ratio 6	R_{t6}	1,000
Axle Ratio	R_a	4,1
Average Effective Rolling Radius	r_r	490 mm
Fuel Density	ρf	0,8540g/cm^3

*Between seconds 25 and 290

The code was run for 150 individuals through 250 generations and produced the results show in Figure 5 and Table 2. The theoretically optimal individual had the values for maximum engine speed at each gear as detailed in Table 2. Figure 5 shows that at no point was the required brake power higher than the brake power produced by the engine.

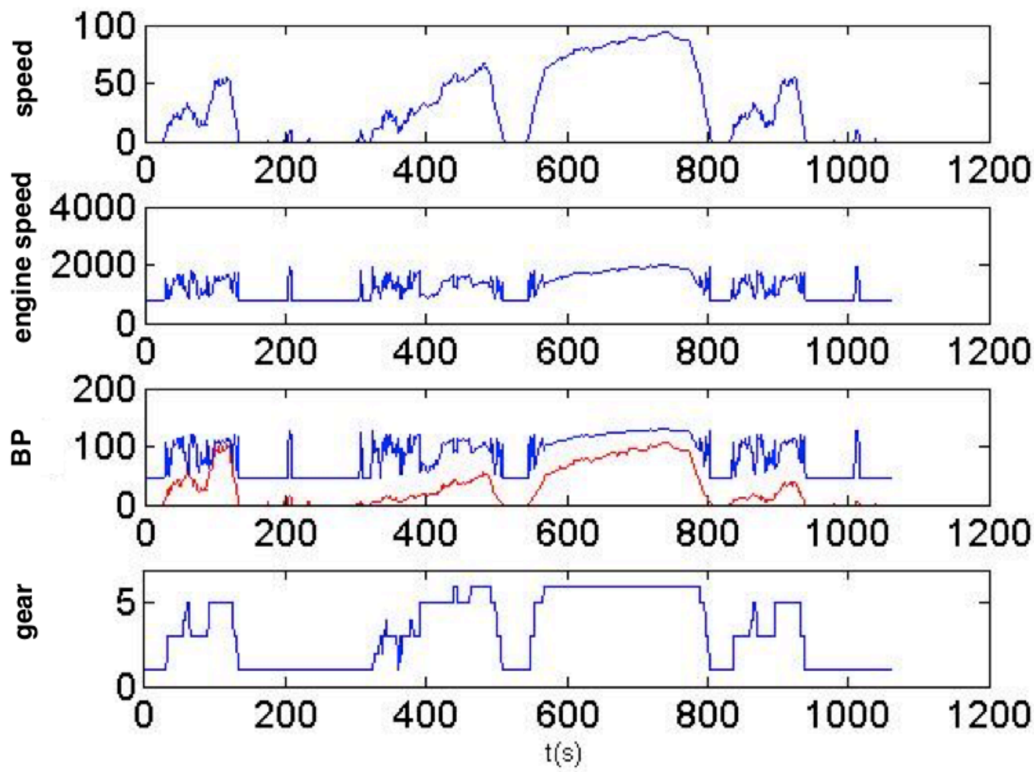

Figure 5: Data for Engine Speed, Brake Power and Gear During the course of the test

Table 2: Maximum Engine Speed per Gear

	Gear					
	1	2	3	4	5	6
Engine Speed (*rpm*)	2000	1350	1800	1250	1650	2050

This optimal individual has a performance rate of 1.53 km/L, which meant an improvement of 13,33% in fuel consumption when compared to a bus changing gears at 2200 *rpm* at every gear while following the same target speed chart.

The optimization was then applied for two routes with $\theta = 1{,}15^\circ$ (route 2) and $\theta = 0{,}74^\circ$ (route 3), resulting in Table 3.

Table 3: Optimization for Routes 2 and 3

Route	FR_{INC} (kgf)	θ	Gear 1 (*rpm*)	Gear 2 (*rpm*)	Gear 3 (*rpm*)	Gear 4 (*rpm*)	Gear 5 (*rpm*)	Gear 6 (*rpm*)	ec (Km/L)
1	400	1,49º	2000	1350	1800	1250	1650	2050	1,5258
2	300	1,15º	1850	1650	1650	1200	1650	2200	1,5724
3	200	0,74º	1500	1450	1250	1350	1300	2050	1,6494

Comparing with the current method applied, which consists in using the engine speed obtained for the most challenging route for all other routes, the Table 4 was obtained.

Table 4: Results compared with the current method

Route	FR_{INC} (kgf)	θ	$ec_{current}$ (Km/L)	$ec_{proposed}$ (Km/L)	$ec_{cutback}$ (%)
1	400	1,72º	1,5258	1,5258	-
2	300	1,15º	1,5258	1,5724	3,0%
3	200	0,74º	1,5258	1,6494	8,1%

The results are as expected since Fuel Consumption (ec) decreases as Inclination do so, and engine speed rearranges for the new conditions. Furthermore, the proposed method presents a maximum cutback of 8,1% when comparing Route 3 with the current method.

5. CONCLUSIONS

The main objective of this work has been successfully achieved, that is to create an optimization code capable of taking as input the brake power and brake specific fuel consumption graphs as well as the target speed required of a specific urban trajectory and optimizing the maximum engine speed for each gear, so that it consumes the least amount of fuel while still being capable of performing appropriately. It's recognized that the consumption achieved is low though, seeing as the usual consumption rate of an urban bus is located in the interval of 2.8 to 3.2 *km/L*. However, seeing as the consumption is still lower comparatively, it is safe to assume that the problem lies in either input curve, most likely the target speed graph, meaning that the course would have a focus on having the bus consume high amounts of fuel and the vehicle performance that assumes 100% of throttle.

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7. RESPONSIBILITY NOTICE

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