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Multiobjective gear shifting optimization considering a known driving cycle

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ABSTRACT. The reduction of the fuel consumption of the vehicles driven by combustion engines is a target of the automakers, governments and drivers. The literature asserts that the adjustment of the driver behavior results in a substantial fuel economy. Specifically, the gear shifting is one aspect of the driver behavior that can be changed by the use of support systems installed in the vehicle that indicate the right moment that the gear must be shifted. The interested community is focused on the development of the algorithms that are implemented in these support systems. These algorithms must be able to arbitrate between two antagonistic objective functions simultaneously: the maximization of the performance and the fuel economy. Thus, this paper demonstrates that it is possible to calculate the trade-off threshold between performance and fuel economy of a vehicle by means of the multiobjective optimization of the gear shifting considering a known driving cycle. To reach this objective, it is created a dynamic model of an automobile base on the literature data; the optimization algorithm implemented is Non-dominated Sorting Genetic Algorithm - II and the driving cycle used is described by the standards ABNT NBR6601:2012 and FTP-72.

Keywords: fuel economy, performance, trade-off, NSGA-II.

Otimização multiobjetivo da troca de marchas em um ciclo de condução previamente conhecido

RESUMO. A redução do consumo de combustível dos veículos com motor a combustão é um objetivo tanto da indústria automotiva, quanto dos governos e dos motoristas. A literatura aponta que a correção da conduta do motorista junto ao seu veículo resulta em uma economia de combustível substancial. Especificamente, a mudança de marchas é um aspecto da conduta do motorista que pode ser alterado por meio do uso de sistemas auxiliares instalados no veículo, que indiquem o momento correto para execução da troca. A comunidade interessada está voltada para o desenvolvimento dos algoritmos implementados sobre esses sistemas auxiliares. Esses algoritmos devem ser capazes de arbitrar simultaneamente sobre duas funções de objetivo antagônicas: as maximizações de desempenho e de economia de combustível. Assim, o objetivo deste trabalho é demonstrar que é possível calcular o limiar de compromisso entre desempenho e economia de combustível de um veículo por meio da otimização multiobjetivo da troca de marchas, considerando um ciclo de condução conhecido. Para isso, é construído o modelo dinâmico de um automóvel baseado em dados da literatura; o algoritmo de otimização empregado é o "Non-dominated Sorting Genetic Algorithm - II" e o ciclo de condução utilizado é descrito pelas normas ABNT NBR6601:2012 e FTP-72.

Palavras-chave: economia de combustível, desempenho, compromisso, NSGA-II.

Introduction

The reduction of fuel consumption is an objective of automobile manufacturers. In addition to the consumer claims (based on monetary and environmental reasons) for efficient power trains, there are several regulations that force the automotive industry to go forward on fuel savings. The Brazilian regulation Inovar-Auto establishes that passenger vehicles in order to be sold in 2017 must consume 18.8% less fuel than those sold in 2011. The Corporate Average Fuel Economy (CAFE) increased the goals of fuel economy for the USA to 24% for passenger vehicle fleet and 35% for light-truck fleet for the period 2011–2025 (AL-ALAWI; BRADLEY, 2014). The European Union has limited the carbon emissions of passenger cars by an average of 130 gCO_2 km^{-1} by 2015 and 95 gCO_2 km^{-1} by 2020, reducing the fuel consumption while the vehicle safety, performance, and comfort must be kept or improved (NTZIACHRISTOS et al., 2014; THIEL et al., 2014). The Canadian provinces of Ontario and Quebec have proposed a 5% penetration target for Electric Vehicles until 2020 in order to reduce the total emissions of road transportation (BAHN et al., 2013). As a final example, Singapore aims at achieving around 7 - 11% of Business-As-Usual carbon emissions reduction until 2020 when compared to 2012, noticing that the road transportation sector is the third major CO_2 producer in the country (HO et al., 2014).

In a practical approach, the fuel consumption and emissions of vehicles are directly influenced by three aspects: traffic infrastructure, vehicle technology and driver behavior. The first aspect (traffic infrastructure) is related to the roundabouts, traffic lights and other types of traffic facilities that aim at supporting the traffic flow. The second approach (vehicle technology) is related to the embedded engineering that focuses on the improvement of the vehicle efficiency, for instance, through the reduction in the vehicle weight, powertrain hybridization/electrification and/or gear shifting assistance/management. Finally, the driver behavior can significantly increase or decrease the vehicle mileage; the pro-fuel saving behavior is termed as "eco-driving". This is not an intuitive behavior for lay people, therefore average drivers need to be instructed, trained and/or assisted in eco-driving (THIJSSEN et al., 2014).

Eco-driving is a decision making process that aims at reducing fuel consumption and emissions. The decisions can be classified as strategic decisions, tactical decisions and operational decisions. Strategic decisions consist in adopting regular maintenance of vehicles. The tactical decisions are related to selection of routes, in order to minimize the fuel consumption (resulting in fuel economy up to 15-40%). Finally, the operational decisions concern the driving ways: if the driver is mild, avoiding hard acceleration, excessive speed and inappropriate gears, the fuel consumption and the emissions are reduced (ALAM; MCNABOLA, 2014).

Some support systems are available to help the driver to drive smoother. These systems can be classified as real-time feedback, short-term feedback and long-term feedback. The real-time feedback systems provide instant information on the operating conditions of the vehicles through the records in mileage-per-volume of fuel in the fuel gauges and, through the shift-advisors and active accelerator pedals. The short-term and long-term feedback systems provide the average performance of the driver (THIJSSEN et al., 2014). The implementation of such systems in new vehicles assists the automakers to implement the regulations for fuel consumption and/or emissions reduction.

Eco driving and gear shifting

It is possible to identify three driving situations: acceleration, cruising and braking. Fuel saving acceleration and cruising are performed with the highest possible gear, so that the engine works in low speeds, which reduces its internal dissipative drag factors. Thus, in general lines, eco-driving operational decisions consist in accelerating moderately, upshifting between 2000 and 2500rpm (which may vary according to the vehicle), keeping the driving pace. Following this behavior, it is expected that up to 26% of the fuel is saved (THIJSSEN et al., 2014).

Moreover, in a recent study about eco-driving, Vagg et al. (2013) proposed an Eco-driving assistant device, which consisted of an aggressive acceleration of light warning and a sound of gearshift indicator. The lights and sounds were designed to be gentle to the driver in order to keep his/her attention on the road. This device was installed in 15 trucks and resulted in an average fuel economy of the fleet of 7.61%, although the variation according to drivers was high (between 0.43 and 12.03% of fuel economy).

Gear shifting techniques

A fixed gear-shifting map normally indicates the gear that must be engaged as a function of two inputs: vehicle speed and throttle valve opening. This map is installed in the transmission control unit (for automated transmissions) or in the gear shift indicator device (for manual transmissions) in which it is obtained the inputs and the subsequent execution or indicated the gear shifting. Naturally, as this map is immutable, there is no flexibility to adapt the gear-shifting strategy to different driving conditions (HA; JEON, 2013). Furthermore, this map can be embedded in a worldwide commercial vehicle platform; however it may not be optimum for each customer needs that can be milder or severer than the standard cycles (HO et al., 2014) that were used to tune it.

An alternative solution is the use of adaptive gear shifting strategies; they are able to change the up-shift and down-shift boundaries as a function of the torque request and traffic conditions. The gear-shifting boundaries are changed within an admissible range, limited by the maximum and minimum engine rotation and the maximum engine torque (HA; JEON, 2013).

The challenging issue about the trade-off between fuel economy and drivability is the nonlinear engine behavior, besides the steep gear ratio of manual/automated transmissions. Furthermore, when the gear shifting occurs, the engine suddenly is driven to different working conditions that might be harmful for the drivability and/or for the fuel consumption. Therefore, stochastic optimization methods have successfully supported the design of optimal gear shift strategy over a given driving cycle.

Dovgan et al. (2013) compared the human driving strategies (concerning throttle, brake and gear management) with the optimum computational strategies derived from a multiobjective optimization algorithm based on the Non-dominated Sorting Genetic Algorithm - II (NSGA-II). A vehicle simulator was used to obtain the volunteer driving strategy before three real-world routes. Although the volunteers were classified in three degrees of expertise, the multiobjective optimization algorithm always achieved the best results in performance and fuel consumption. A disadvantage of the optimum solutions obtained are the uncomfortable jerks (DOVGAN et al., 2012). They occurred because this optimization is focused on accomplishing the vehicle displacement instead of the vehicle speed and under this condition the best fuel economy is achieved by imposing low frequency engine pulses around 0% for throttle (almost zero fuel consumption), and high opening throttle (high fuel consumption but high efficiency, resulting in an optimal overall fuel consumption).

Research gap

From the literature reviews it is possible to identify a research gap that consists in the absence of a methodology that identifies the trade-off between fuel consumption and vehicle performance of a gear shifting strategy. This trade-off can be identified through an optimization process based on three premises: (a) the algorithm must be based on a known driving cycle, (b) this cycle can be standardized, inserted by the driver or acquired from the vehicle, (c) the algorithm must follows the driving cycle objective velocity avoiding jerks because of the discontinuous use of the engine.

Objectives

This paper aims to contribute by demonstrating how to trace the trade-off between the vehicle performance and fuel consumption for two different gear shifting strategies. In order to achieve this goal, the standard driving cycle of ABNT NBR6601:2012 is used as the input for an optimization algorithm based on the NSGA-II. The vehicle dynamic model is oriented to follow as close as possible the driving cycle velocity. The optimization targets are to maximize the performance and the mileage per liter of fuel simultaneously.

Material and methods

Longitudinal vehicle dynamics

The Longitudinal Vehicle Dynamics is a strict approach of the Vehicle Dynamics by focusing on the analyses of performance and energy consumption of an automobile subjected to a driving cycle. The classic model of Longitudinal Vehicle Dynamics consists of an automobile that travels through a flat road. It must be considered that the road is tilted about an α angle in relation to the horizontal; the instantaneous vehicle speed is v and there is an acceleration due to gravity g that acts in the vehicle mass m_v. Thus, it is possible to apply the Newton's Second Law of Motion on the vehicle center of mass as described by the equation (1) (GILLESPIE, 1992).

$$m_v \frac{d}{dt} v(t) = F_t(t) - \left(F_a(t) + F_r(t) + F_g(t)\right) \quad (1)$$

In the equation (1) F_t is the Traction Force, F_a is the Aerodynamic Drag, F_r is the Rolling Resistance and F_g is the Climbing Resistance. Each force is described in the following subsections.

Traction force

The Traction Forces can be produced by the powertrain or by the brakes. The powertrain produces positive Traction Forces (while the throttle is open) and negative Traction Forces (while an engine braking occurs). The powertrain Traction Force (F_{te}) is expressed by the equation (2), which applies the Newton's Second Law in a powertrain composed of engine, clutch, transmission, differential and wheels:

$$F_{te} = \frac{T_e N_t N_d}{r_w} - [(I_e + I_t)(N_t N_d)^2 + I_d N_d^2 + I_w] \frac{d}{dt} \frac{v}{r_w^2} \quad (2)$$

where r_w is the wheel radius, T_e is the engine torque, N_t is the transmission ratio, N_d is the differential ratio, I_e, I_t, I_d and I_w are the rotational inertias of the engine, the transmission, the differential and the wheels, respectively. I_t and N_t are functions of the selected gear. Due to the high level of complexity of the engines, for the sake of simplicity T_e can be obtained from an experimental lookup table as a function of the engine speed and the throttle angle. The specific fuel consumption of the engine can be calculated in the same way. The brakes only produce negative Traction Forces. They can be considered ideal since the brake lock and tire slip are neglected due to the drive cycle is based on the trivial driving conditions. Thus, the component of Tractive Force resulting from the brakes (F_{tb}) is written in equation (3):

$$F_{tb} = \frac{T_b}{r_w} \quad (3)$$

where T_b is the brake torque. Therefore, the full equation of the Traction Force is expressed by the equation (4):

$$F_t = \frac{T_e N_t N_d + T_b}{r_w} - [(I_e + I_t)(N_t N_d)^2 + I_d N_d^2 + I_w]\frac{d}{dt}\frac{v}{r_w^2} \quad (4)$$

Aerodynamic drag

When the air penetrates the front area of the vehicle, high pressure zones are generated in this area. As the streamlines move downward in the direction of the rear side, zones of low pressure are created behind the vehicle. Thus, this pressure differential generates a longitudinal resulting force called Aerodynamic Drag (GILLESPIE, 1992), and is defined by the equation (5):

$$F_a = \frac{1}{2}\rho C_d A(v + V_w)^2 \quad (5)$$

in which ρ is the air density, C_d is the drag coefficient, A is the vehicle frontal area and V_w is the positive wind speed against the vehicle movement. The drag coefficient is obtained empirically and is constant for the speed ranges of the standard automobiles.

Rolling resistance

The Rolling Resistance is the dissipative effect caused by the friction and the tire carcass deformation in contact with the road. This force is defined by the equation (6) as a function of the rolling resistance coefficient (f) and the component of the gravity force normal to the road.

$$F_r = f.m_v.g.cos(\alpha) \quad (6)$$

The equation (7) describes f considering the vehicle speed and weight, the tire type and its inflation pressure (p) (GENTA, 1997):

$$f = \frac{K}{10^3}\left(5.1 + \frac{5.5 * 10^5 + 90 m_v g cos(\alpha)}{p} + \frac{1100 + 0.04 m_v g cos(\alpha)}{p} v^2\right) \quad (7)$$

where K is a constant as a function of the tire type (0.8 for radial and 1 for non-radial).

Climbing resistance

The component of the gravitational force parallel to the road plane is called Climbing Resistance. As expressed by the equation (8), if α is positive, the car is moving uphill and the Climbing Resistance acts against the movement.

$$F_g = m_v.g.\sin(\alpha) \quad (8)$$

Multiobjective genetic algorithm

The multiobjective genetic algorithms are useful for real-world optimization problems that cannot be solved as a function of a single objective function. Generally, the solution consists of a family of points that indicates the line or surface that is the trade-off between the optimization objectives. Most of the multiobjective genetic algorithms use the domination concept to steer the solutions towards the best trade-off (BANOS et al., 2011). In a population of solutions, the solution "a" dominates the solution "b" if "a" is better than "b" in all the objective functions. The solution front that is dominated by no other solution is called "first non-dominated front"; this front is as close as possible to the ideal trade-off front. Similarly, the solutions dominated by only one other solution compose the "second non-dominated front" and so on. (DEB, 2014).

The NSGA-II starts with an initial population chosen at random, composed of "n" members. This population is sorted among non-dominated fronts. Then, binary tournament selections are used in order to select the mates that generate the first offspring "n" sized after the application of recombination and mutation operators. A binary tournament selects two members randomly; if the members are categorized in different non-dominated fronts, the one that is closer (or inside) the first non-dominated front prevails; however, if the members are categorized in the same non-dominated front, the member in a less crowded region, prevails for the sake of diversity (DEB, 2014).

The looping part of the algorithm starts from the union of the parental population and the offspring into one single group of size "2n". This group is sorted among non-dominated fronts and they are ranked inside the fronts according to the crowding distance. Then the last "n" members are excluded and the remaining members compose the next parental population. Finally, the binary tournament selections are used in order to select the mates that generate a new offspring, considering the recombination and mutation operators. As soon as this new offspring is ready, the looping part restarts although a stopping criterion is reached (DEB, 2014).

Simulation configuration

The simulations are based on the parameters of a typical Brazilian popular automobile equipped with a 1 liter engine. Its respective gear ratios, gear shifting speeds specified by the manufacturer and further data are available in the Table 1. The engine torque map and specific fuel consumption map are shown in the Figure 1. The first is the lookup table that outputs the engine torque as a function of the engine speed and the throttle opening. This engine torque is one of the inputs of the Traction Force evaluation. This map is normally obtained from an engine dynamometer test. The same test also derives the second map, which is the lookup table that outputs the specific fuel consumption of the engine as a function of the engine speed and torque. From the engine torque, the engine speed and the specific fuel consumption of the engine, it is possible to calculate both instant and total fuel consumption applying operations of dimensional analysis and integral operator, respectively.

Table 1. Typical Brazilian popular car parameters (adapted from ECKERT et al., 2015).

Parameter	*Magnitude*	*Parameter*	*Magnitude*
Vehicle Mass m_v	1206 [*kg*]	Differential Ratio / Inertia	4.87 / 7.44e-4 [kgm^2]
Tire Radius r_w	0.334 [*m*]	1st Gear Ratio / Inertia	4.27 / 1.791e-3 [kgm^2]
Tire Inflation Pressure p	30 [*psi*]	2nd Gear Ratio / Inertia	2.35 / 2.415e-3 [kgm^2]
Tire Constant K	0.8 (radial)	3rd Gear Ratio / Inertia	1.48 / 3.421e-3 [kgm^2]
Frontal Area A	1.8 [m^2]	4th Gear Ratio / Inertia	1.05 / 4.782e-3 [kgm^2]
Drag Coefficient C_d	0.33	5th Gear Ratio / Inertia	0.80 / 1.07e-03 [kgm^2]
Air Density ρ	1.226 [$kg\ m^{-3}$]	1st / 2nd Gear Speed	15 [$km\ h^{-}$]
Engine Inertia	1.58e-1 [$kg\ m^{-2}$]	2nd / 3rd Gear Speed	30 [$km\ h^{-}$]
Clutch Inertia	3.90e-3 [$kg\ m^{-2}$]	3rd / 4th Gear Speed	50 [$km\ h^{-}$]
Other Rotating Inertia	1.724 [$kg\ m^{-2}$]	4th / 5th Gear Speed	72 [km h^{-}]

During the simulations, the vehicle is subjected to the Brazilian Urban Driving Cycle described by the standard ABNT NBR6601:2012. This standard is based on the US FTP-72 (Federal Test Procedure), so it is worth mentioning that the analyses performed in this paper are not restricted to the Brazilian issues. There are no descriptions of the road grade or wind speed, thus these variables are neglected in the mathematical model.

Since the longitudinal dynamic equations of the vehicle are set and the parameters are defined, it is possible to implement the longitudinal model of the vehicle through block algebra. The software MATLAB/Simulink assisted in the implementation. The solver used is the ODE113 (Adams-Bashforth-Moulton method for solving differential equation), in which presents low numerical error in discontinuities, as solver demonstrated by Jasion et al. (2011) in a study about the error and performance of some numerical solvers in a collision problem. In the present paper, the event of gear shifting imposes discontinuities, and as the gears are shifted many times along the driving cycle, the ODE113 is suitable.

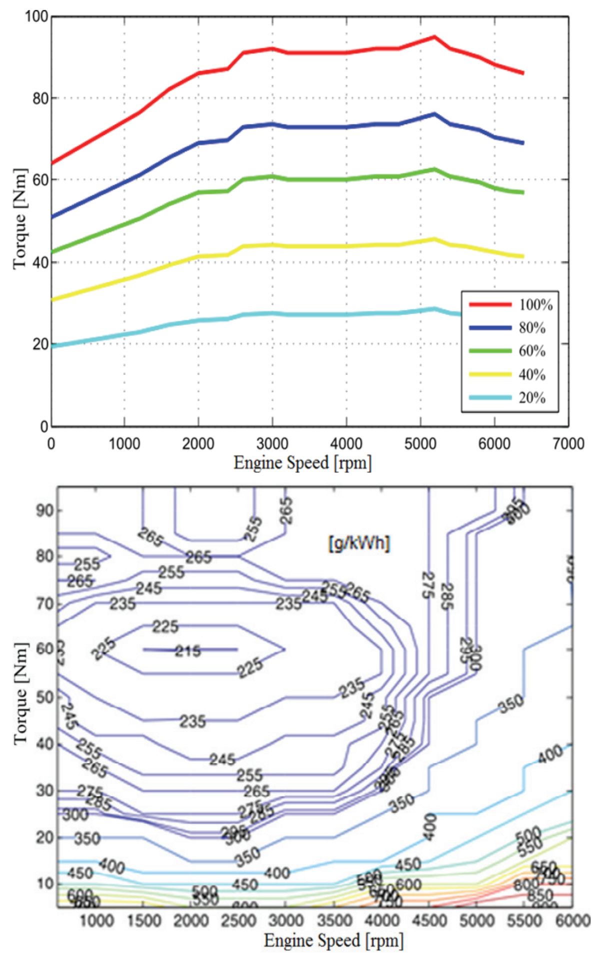

Figure 1. On the top, it is exposed a typical torque curve of a 1 liter engine as a function of the throttle opening. The specific fuel consumption map is pictured on the bottom (adapted from ECKERT et al., 2015).

In parallel to the mathematical model, a logic was implemented in order to emulate the driver to feed the mathematical model and make it to trace the driving cycle. It works by comparing the instant drive cycle speed to the instantaneous speed simulated; the difference between them is divided by a time delta, resulting in the objective acceleration. This time delta is tuned as a function of the time response desired, herein defined in 0.5s. The objective acceleration is then inputted in a reverse dynamic problem that returns the objective torque. If this torque is positive, it is attributed to the engine torque (T_e), otherwise it is attributed to the brake torque (T_b), composing the Tractive Force. Finally the Tractive Force is inputted in the longitudinal dynamic system of the vehicle and the response is obtained. If the simulated automobile reaches a gear shifting point, the actual gear is disengaged in 0.5s and the next gear is engaged in 0.5s, in a total of 1.0s of gear shifting time.

The strategies of gear shifting chosen are the speed based (SB) and the fuel consumption map based (FCMB). In this paper, the SB strategy consists of shifting the gear as soon as a gear shifting speed is transposed in ascending or descending way. Moreover, the gear shifting speeds are constants and must be set before the beginning of each simulation. The ascending gear shifting speeds are the parameters to be optimized; the descending gear shifting speeds are always of 5 km h^{-1} lower than the ascending gear shifting speeds in order to avoid fitful gear shifting.

The FCMB strategy implemented in this paper consists of shifting the gear as soon as the next gear is able to provide satisfactory torque with better specific fuel consumption. As the gear shiftings imply in torque gaps, immediately after their executions, loss of performance and increases of fuel consumption may occur. Thus it is necessary to define a ratio between the specific fuel consumption of the next gear and the current gear; this ratio ensures the gear shifting results in a global fuel consumption reduction. This ratio is called gear shifting ratio herein. Between each gear there are an ascending and descending gear shifting ratio to avoid fitful gear shifting, similar to the previous strategy, but now both ascending and descending ratios are the parameters to be optimized.

A Referential Simulation is performed based on the gear shifting speeds specified by the manufacturer (described in Table 1). The results regarding the travel distance and fuel performance achieved by this setup are the minimum constraints for the optimization processes that follow.

The first optimization processes aims at optimizing the SB strategy. In this case, the four ascending gear shifting speeds are the chromosome genes of each member of the NSGA-II algorithm population. The second optimization process aims at optimizing the FCMB strategy. In this case, the four ascending and the four descending gear shifting ratios are the chromosome genes of each member of the NSGA-II algorithm population.

Both optimization processes contain a population of 20 members and the stopping criterion is based on the convergence stagnation: if the best travel distance and the best mileage per liter of fuel among the members of the "first non-dominated front" remain the same for 50 generations, the optimization process is assumed to have converged and the NSGA-II algorithm is stopped.

Results and discussion

In the Referential Simulation, the speed profile of the standard urban cycle is satisfactorily traced by the simulated vehicle: in the Figure 2 (left side) it is possible to notice how the instantaneous speed of the simulated vehicle overlaps with the instantaneous speed proposed by the Brazilian urban cycle. Also in the Figure 2 (right side) it is possible to observe the gears that are used by the simulated vehicle in the Referential Simulation to accomplish the driving cycle. It is possible to notice that there is no fitful gear shifting: the gears are used sequentially along the time. Finally, although the Brazilian urban cycle is 11,990.0m long, the simulated vehicle travels 11,898.0m performing 14.056 km l^{-1} in the Referential Simulation.

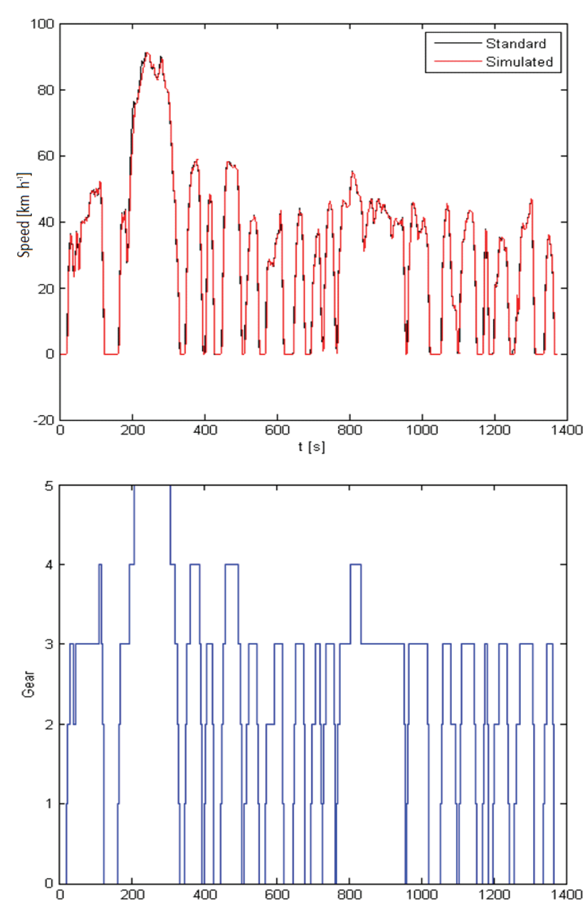

Figure 2. Speed and gear profiles of the referential simulation.

Based on the results of the Referential Simulation as minimum constraints, the multiobjective NSGA-II optimizations for SB and FCMB gear shifting strategies were performed. The final generations obtained from the NSGA-II, for both strategies, are plotted in the Figure 3, concerning travel distance and mileage per liter of fuel, and together with the results of the Referential Simulation. It is possible to distinguish the non-dominated fronts for SB (round icons) and FCMB strategies (lozenge icons). Besides, these fronts successfully expanded from the Referential Simulation results in the direction of the simulation targets, maintaining the trade-off threshold. As a last remark, the non-dominated front of the FCMB strategy is better than the front of the SB strategy, for both optimization targets.

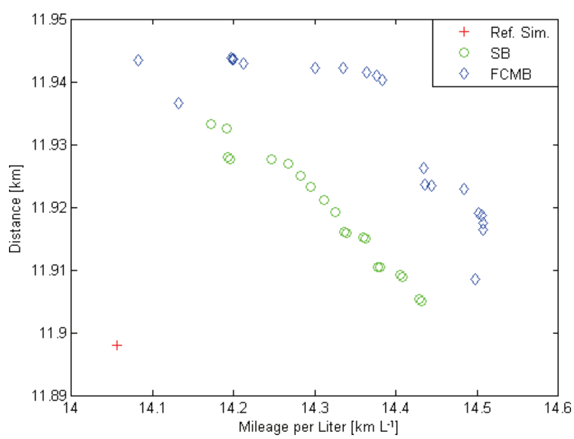

Figure 3. Referential Simulation and non-dominated fronts of SB and FCMB.

The setup and the details of the Referential Simulation and of the most relevant members of the final non-dominated front for the SB strategy are described in the Table 2. In addition, the details of the most relevant members of the final non-dominated front for the FCMB strategy are described in the Table 3. It is possible to notice that the gear shifting speeds from the 4th to the 5th gear (obtained from the VB strategy) are higher than the top speed of the driving cycle (91.2 km h^{-1}). Besides, the gear shifting ratios between the 4th and the 5th gears (obtained from the FCMB strategy) take values that make unfeasible the use of the 5th gear. Thus the gear shifting from the 4th to the 5th gear was rejected by both optimization processes.

The Figure 4 shows the speeds and the gear profile of the top speed section of the driving cycle for the simulations detailed in the Table 2 and in the Table 3. It is possible to check that even in the highest speed stretch (between 240 and 250s) the 5th is used exclusively by the Referential Simulation, coherently with the rejection of the 5th gear by the optimized strategies. As another remark, it is possible to notice that the SB strategies, Best Compromise and Best Mileage, are those that badly trace the standard cycle between 50 km h^{-1} and 75km h^{-1}, because in their case the 3rd gear is shifted for the 4th gear sooner than others. On the other hand, all optimized strategy traces the standard cycle better than the Referential Simulation at speeds higher than 75km h^{-1} because they do not shift from the 4th to the 5th gear.

Although the FCMB strategy presents a better non-dominated front, there are fitful gear shiftings when this strategy is used. This means that while the Referential Simulation and the SB strategy present a sequential gear shifting along time, the FCMB may present unstable gear shifting. They occasionally occur, but some unstable gear shiftings can be noticed in the selected stretch of the gear shifting profile (between 1260s and 1270s), as seen in the Figure 5.

Table 2. Details of the main results of the Referential Simulation for the SB strategy.

			Gear Shifting Speed [km h^{-1}]				Travel Distance [m]	Mileage per liter of fuel [$km\ L^{-1}$]
			1st / 2nd	2nd / 3rd	3rd / 4th	4th / 5th		
Referential Simulation		Up Shift	15	30	50	72	11,898.0	14.056
		Down Shift	10	25	45	67		
SB Strategy	Best Travel Distance	Up Shift	18.60	21.51	75.31	97.21	11,933.2	14.172
		Down Shift	13.60	16.51	70.31	92.21		
	Best Compromise	Up Shift	18.59	21.79	51.79	124.13	11,919.2	14.324
		Down Shift	13.59	16.79	46.79	119.13		
	Best Mileage	Up Shift	18.63	21.81	44.59	97.21	11,905.0	14.431
		Down Shift	13.63	16.81	39.59	92.21		

Table 3. Details of the main results of FCMB strategy.

			Gear Shifting Ratio [-]				Travel Distance [m]	Mileage per liter of fuel [$km\ L^{-1}$]
			1st / 2nd	2nd / 3rd	3rd / 4th	4th / 5th		
FCMB Strategy	Best Travel Distance	Up Shift	1.079	1.164	1.358	6.296	11,943.7	14.196
		Down Shift	1.019	1.127	1.288	1.400		
	Best Compromise	Up Shift	1.094	1.134	1.288	4.430	11,940.3	14.383
		Down Shift	1.019	1.127	1.288	1.393		
	Best Mileage	Up Shift	1.077	1.163	1.358	8.780	11,916.4	14.506
		Down Shift	1.007	1.026	0.364	6.296		

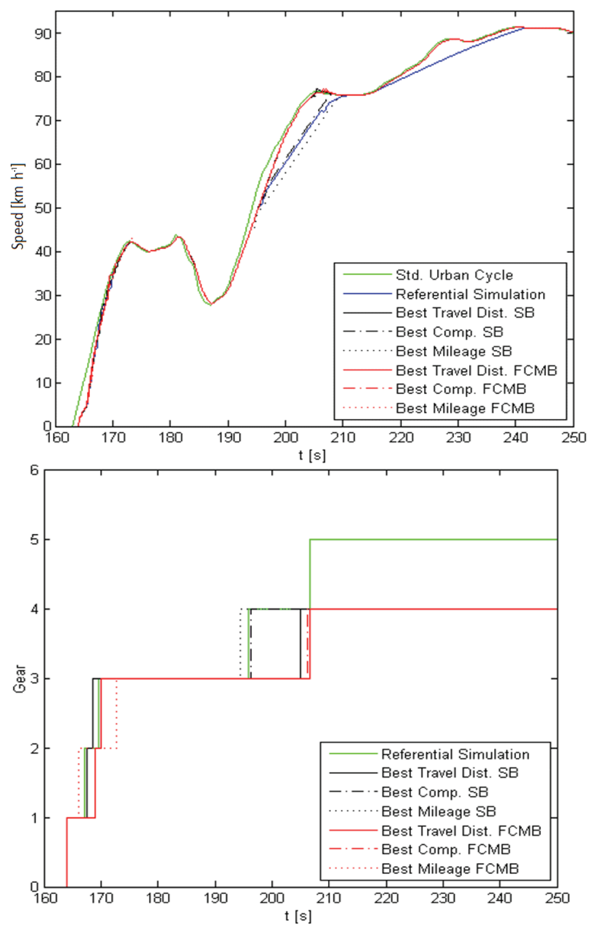

Figure 4. Speed and gear profiles of the referential simulation and of the FCMB and SB main results.

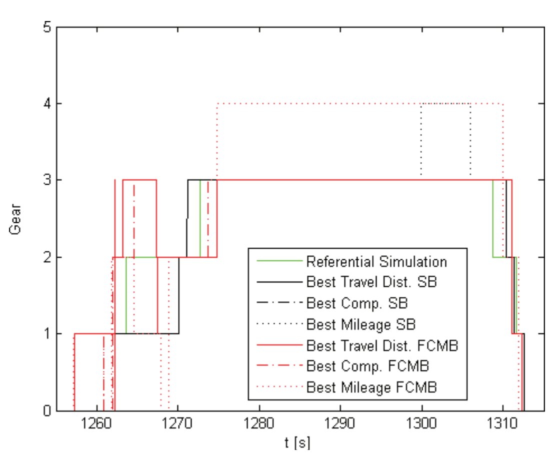

Figure 5. Comparison between gear profiles during the occurrence of fitful gear shiftings.

By adding up the results, the optimized FCMB strategy presented the best trade-off between performance and fuel economy. This strategy tends to prevail, because it compares the specific fuel consumption resulting from the gear in use to the specific fuel consumption that would be executed by the following gear, and decides if it is time to shift instead of shifting the gears automatically when a shifting speed previously defined is reached. On the other hand the FCMB strategy eventually executes fitful gear shiftings. It may result in moments of comfortless riding in the real application and a filter must be studied to future researches.

It is possible to point out future studies that will help to accomplish the identified research gap. These gear shifting strategies and optimization technique can be implemented in an experimental setup on the real roads. The driving cycle can be obtained in real time, according to the real driving routines, while the optimization process can be run in a parallel thread. Finally, the gear shifting can be shown to the driver by an interface (in the case of manual transmissions) or can be directly executed by an actuator (in the case of automated transmissions).

Conclusion

The Referential Simulation executed from a model based on the equations and parameters described in the literature succeeded in tracing the ABNT NBR6601:2012 / FTP-72 urban driving cycle. Its results on travel distance and mileage per liter of fuel provide minimum constraints reliable for the multiobjective optimization of the gear shifting strategies.

It is possible to indicate the trade-off between performance and fuel economy through NSGA-II. Besides, the optimized non-dominated fronts of the SB and FCMB strategies presented better results than the Referential Simulation. This demonstrates the success of the merger between these gear shifting strategies and the NSGA-II.

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