AUTOMOTIVE ENERGY EFFICIENCY IMPROVEMENT APPLYING START & STOP SYSTEM AND ALTERNATOR OPERATION STRATEGIES

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ABSTRACT

With the formidable growth of the automotive industry, also came the concern with the rise of greenhouse gas emissions and the importance of this sector to develop innovative technologies to increase energy efficiency, reducing fuel consumption and consequently mitigating CO_2 emissions. This research aimed at the experimental analysis of the energy consumption and CO_2 reduction comparison applying Stop & Start system and alternator operations strategies. One of these alternator operational strategies is based on its mechanical and electrical coupling and decoupling due to a pulley integrated to an electromagnetic clutch in certain predetermined circumstances. This operation was elaborated from the conventional strategy that contemplates only the electrical decoupling, known as "smart alternator". The tests were performed on a vehicle in the urban and highway cycles (FTP75 + HW) in order to evaluate its operational characteristics, as well as obtaining the energy consumption of each configuration. Compared to the baseline configuration, the results presented energy consumption reductions of 2.38% and 3.56%, using separately the Start & Stop system and alternator operating strategies, respectively, and reduction of 4.91% when combined.

INTRODUCTION

Global concern about rising global average temperatures has led several countries to adopt measures that can minimize the effects of pollution on future generations. To do so, legislations have been created so that, mainly, the industries have parameters to be followed and can always work seeking to reach the governmental targets.

In Brazil, this scenario is not different. During the period of 2013 to 2017 the program of Incentive to Technological Innovation and Chain of Auto-vehicles Production, denominated INOVAR-AUTO was in force. When finalized, there was already a proposal for its successor, what would become ROTA 2030, which like INOVAR-AUTO, are measures put by the government so the companies in the automotive industry follow and fulfill minimum requirements of energy efficiency and emission of greenhouse gases (GHG), and those that exceed those requirements will have fiscal incentives. In order to achieve ROTA 2030 targets, it is necessary to invest heavily in research and development in the automotive sector, thus new innovative technologies may be installed in vehicles within the next few years.

Given the need to apply new technologies to improve energy efficiency in light-duty internal combustion vehicles, the objective of this article is the experimental comparative analysis of isolated and combined Stop & Start and alternator technologies with mechanical and electrical decoupling strategies. [1] [2]

1. LITERATURE REVIEW

Among the trends to improve automotive energy efficiency, the Start & Stop (S&S) system has gained prominence and increased application by car manufacturers around the world. This system consists of automatic shutdown of the internal combustion engine of the vehicle at zero speed (stops on traffic signals, intersections and / or slow traffic). The vehicle's engine is then turned back on when the driver intends to retake the movement (driving the clutch pedal in manual vehicles or disengaging the brake pedal in automatic vehicles).

For the Start & Stop operation system, automotive components with differentials are required to ensure the durability of the vehicle subsystems throughout the car's operating cycle. Amongst the components, there is a need for more robust starting motors and special batteries to withstand sequential loading and unloading cycles, since at each successive start of the engine (system characteristics), energy consumption is demanded from the vehicle battery.

The classical energy balance of internal combustion engines has shown that friction and auxiliary accessories can consume a large part of thermal energy [3].

Among the auxiliaries, the alternator significantly influences the increase in the energy consumption of the internal combustion engine, which can be attributed to this component from 4 to 6%. In this way, improving the efficiency of the alternator reduces energy loss. Thus, high efficiency alternators can reduce energy or fuel consumption from 0.5% to 2.0%. [4]

In addition to the evolution of the alternators in terms of efficiency strategies were also developed for the electronic management of electric power generation. In the electric power management of the vehicle, the IBS (Intelligent Battery Sensor) technology has the main function of monitoring the battery parameters, such as current, voltage and temperature of the battery. From this data it is possible to estimate other important parameters as the SOC (State of Charge). [5]

The IBS is an electronic module integrated with the negative battery terminal. The collected and calculated information is sent by the local interconnection network (LIN), and it is used by the vehicle electronic control unit (ECU). [6]

The IBS is a relevant sensor, as it continuously performs the analysis and supply of the main parameters such as the battery state of charge (SOC) and the battery degradation (SOH) that are inputs for vehicular control systems. The “smart alternator” technology is the result of the high efficiency alternator combined with LIN and IBS. The alternator coupling and uncoupling to the crankshaft pulley are subject to the estimated battery parameters by the IBS. Another system that directly depends on the parameters determined by the IBS, mainly the state of charge of the battery (SOC), is the "Start & Stop" (S & S). If there are no safe conditions for shutting down and starting the internal combustion engine, the "Start & Stop" strategy is inhibited.

Another strategy associated with the alternator is its mechanical and electrical decoupling that is achieved with the patented prototype alternator [1] [2] used in this study, representing an attractive solution to increase the vehicular efficiency energy. From this strategy, complete unloading of the crankshaft shaft is allowed. For this to occur, this alternator has an electromagnetic clutch coupled to its pulley. The strategy is to decouple the alternator from the crankshaft when the battery is sufficiently charged to support the operation of the vehicle. In suitable conditions, in terms of electric power generation, the alternator is coupled. [3].

2. METHODOLOGY

2.1. Experimental Apparatus

In this study, a vehicle with the Start & Stop system was used, in this way, with each condition characterized as idling, its internal combustion engine was shut down.

For the Start & Stop system works properly, a number of parameters are controlled so the vehicle operates on a regular basis and maintains occupant safety throughout the operation.

In zero-speed vehicle condition, the S & S acts primarily if the gear is in neutral (for "manual vehicles") or with the guarantee that the brake will have a certain vacuum pressure for ("automatic vehicles"). The Start & Stop system depends, in addition to the idling condition, on the engine temperature, which can be observed and evaluated through the water temperature. In other words, in the first phase of urban cycle, the Stop & Start function will not turn off the engine until the water temperature reaches the minimum required. In addition, the driver's door and bonnet must be closed; the driver's seat belt must be buckled; the vehicle must not be in an adaptive fuel condition and, finally, no serious error codes can be found in the electronic control units (indicated mainly by warning lights on the panel). In contrast, the alternator with the coupling and uncoupling strategy essentially depends on the battery charge level.

From a 150A high efficiency alternator associated with an electromagnetic clutch system associated with its pulley was developed the prototype of the alternator with mechanical decoupling used in this study, as shown in Figure 1. [1] [2]

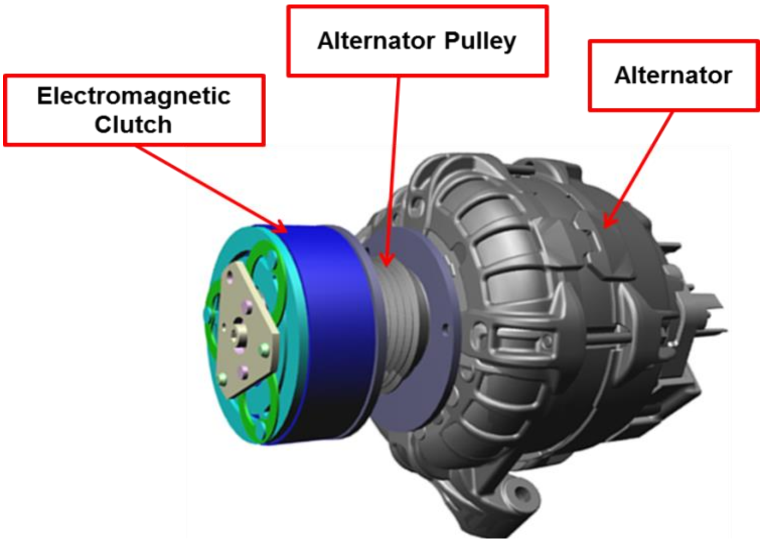

Figure 1 - Prototype alternator with electromagnetic clutch [7].

The great distinction between the alternator equipped with the electromagnetic clutch and the high efficiency smart alternator is that the former allows both the electric and the mechanical decoupling, while the latter allows only the electric decoupling. As mentioned in the introduction, the operation of the internal combustion engine and the state of charge of the battery are the main variables for the alternator decoupling and coupling. When the decoupling occurs, the alternator can be mechanically and electrically completely deactivated. Thus, the charge of the electromagnetic field generated by the electric power of the alternator rotor and the inertial charge of the mass of the rotating alternator are deactivated from the crankshaft axis.

The ECU (electronic control unit) is the control system that receives the data from the prototype alternator. Also, a shunt with a ratio of 150A to 60mV was installed for the analysis of the voltage and electric current coming from the prototype alternator. With a pre-established strategy and based on the CAN network data such as vehicle speed, engine speed, battery charge status (earned by IBS) and acceleration pedal percentage, the ECU coordinates the coupling and decoupling operations of the alternator.

The vehicle used in this study has an ECU that controls the fuel injection and ignition of the internal combustion engine, as well as the activation of the S&S system and the deactivation or activation of the smart and cycling alternator functions.

2.2. Alternator coupling and decoupling strategies

The coupling and decoupling strategy of the alternator is given by a software that controls two relays that are essential for the electrical power of the electromagnetic clutch of the alternator. One of these relays is commissioned to the mechanical coupling, while the other drives the alternator's electric coupling. [3].

According to the parameters, such as the battery charge level, engine speed (rpm), vehicle speed and position of the accelerator, from the CAN the tripping entities enable the electric power of the electromagnetic clutch. In this way, the decoupling is guaranteed.

The Figure 2 illustrates the alternator prototype operational control system and data acquisition processes.

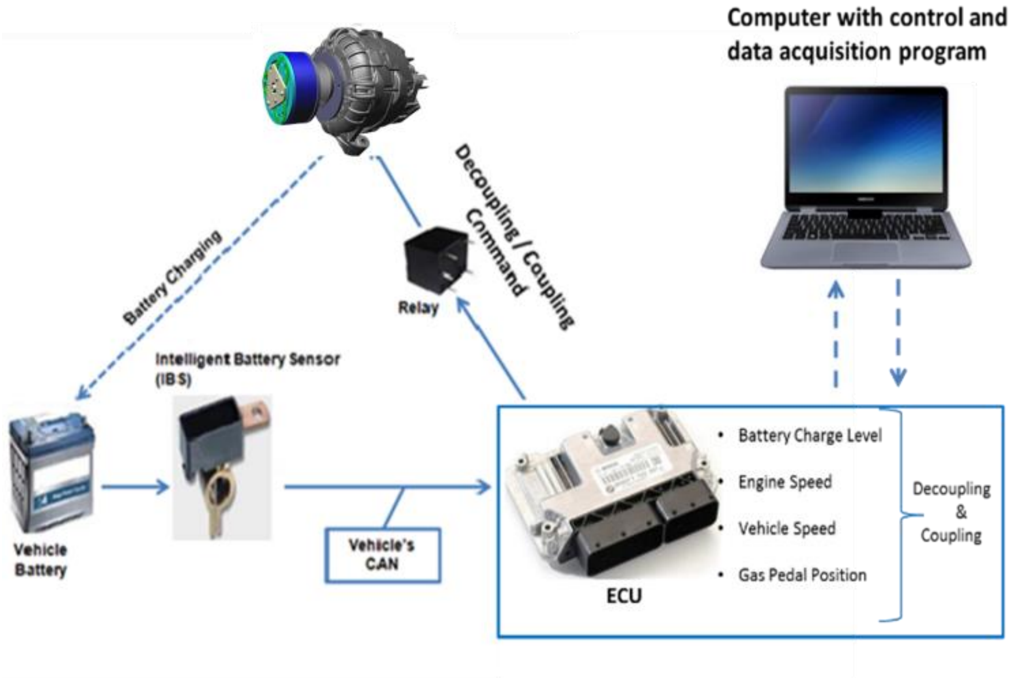

Figure 2 - Alternator prototype operational control system and data acquisition scheme [7]

In acceleration periods, the decoupling of the alternator is assuredly carried out with the battery level higher than or equal to 75% along with the accelerator position, with minimum variations in idle speed (approximately 850 rpm). During deceleration periods, battery energy regeneration occurs regardless of its state of charge. In addition, in periods of acceleration, with a percentage of the battery charge level below 75%, the alternator is still connected. If the data confirms that the vehicle is decelerating, the clutch mechanically connects to the alternator and after two seconds allows the flow of electrical energy to the battery. This lag occurs so the impact on the engine and transmission assembly is reduced. The same analysis is performed for the decoupling, where the electrical decoupling precedes in a second the mechanical decoupling.

In order to evaluate and compare the results of the combined effects of the alternator with the mechanical decoupling and Stop & Start strategies, Table 1 shows the tests performed. It is important to note that every time the alternator with mechanical decoupling is triggered, the smart alternator strategy is activated. Thus, the baseline configuration was fixed as the alternator always coupled (alternator strategies off and S & S deactivated).

Table 1 - Experimental tests configurations and following descriptions

Configurations		Description
1	Baseline	Start & Stop system OFF and alternator strategies OFF
2	S&S only	Start & Stop system ON and alternator strategies OFF
3	S&S and cycling alternator	Start & Stop ON and mechanical cycling alternator strategy ON

3. RESULTS

3.1. Baseline operation

The Figures 3 and 4 present the mainly data acquisitions parameters for the urban and highway cycles: battery charge, vehicle speed, engine speed (rpm), radiator fan action and engine temperature, related to the baseline configuration.

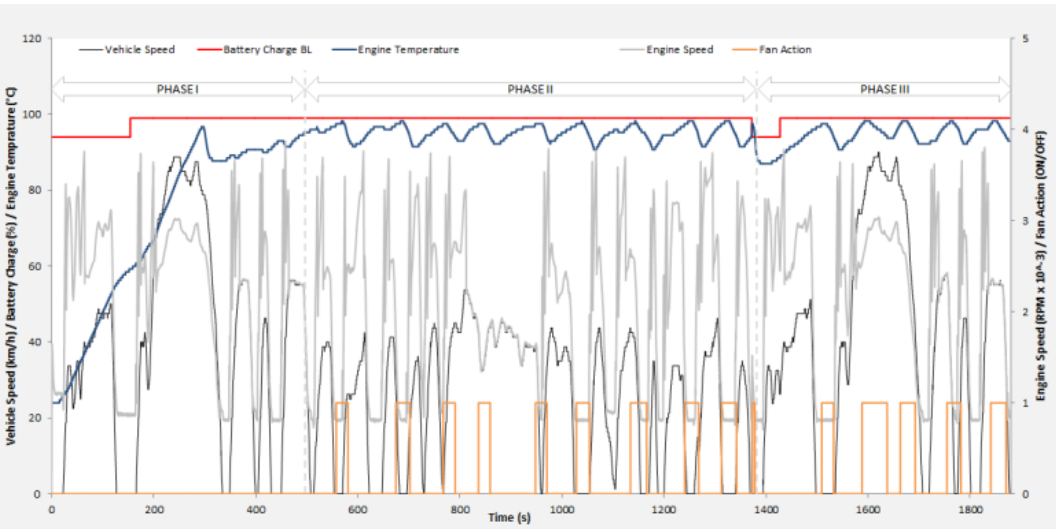

Figure 3 - Baseline configuration in the Urban cycle.

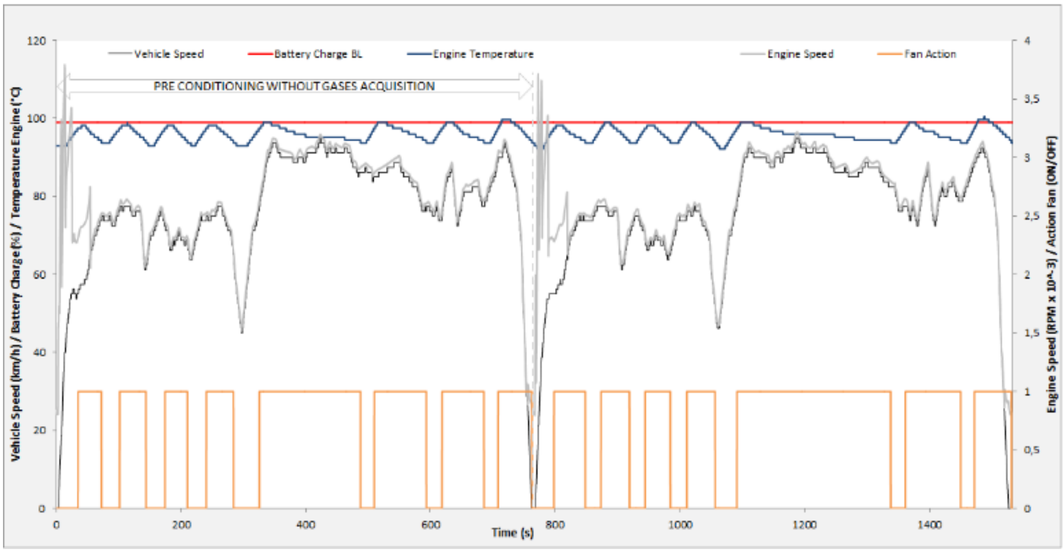

Figure 4 - Baseline configuration in the Highway cycle.

During the urban and highway cycles the alternator, in constant coupled operation, the battery state of charge remains closer to 100%. Also, the fan radiator is one of the main consumers of energy and its operation was monitored all the time during the test in order to verify the influences on battery charging.

3.2. Start & Stop system isolated analysis

As the S&S configuration strategy depends on the idle operation and vehicle at zero speed (0 km/h), this analysis is concentrated only in the urban cycle, because in highway cycle there are not occurrences of these vehicle conditions. The battery charge status maintained at the same level (100%). In S&S only, isolated configuration, the alternator operates in a conventional way in terms of energy generation. The Figure 5 presents the S&S isolated configuration during urban cycle.

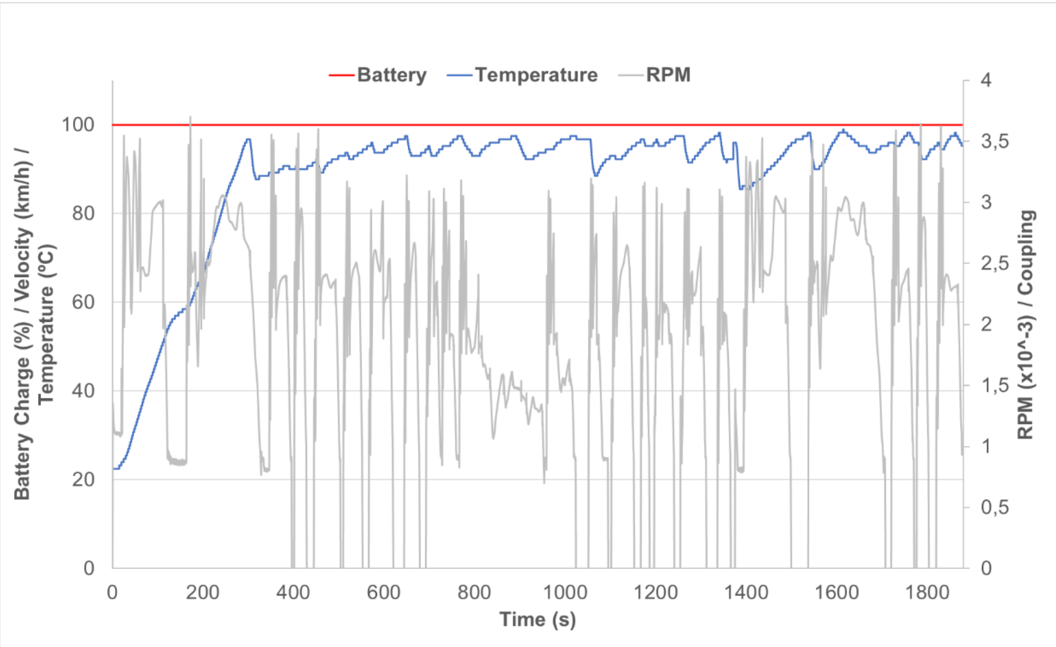

Figure 5 - S&S strategy and main parameters results in urban cycle

3.3. Start & Stop system and cycling alternator

The configuration that combines S&S and Cycling Alternator (alternator decoupling/coupling mechanically) is shown in Figure 6. It is possible to note that there is no shutdown of the internal combustion engine as a function of the engine water temperature (less than 40 °C). In the meantime, the alternator has been decoupled since the first idle period and subsequent accelerations. As the functions of the Cycling Alternator configuration are based on the smart alternator strategy, the charging of the battery occurs at the same conditions during cut off periods mainly (deceleration with transmission engaged). Because of these characteristics, in configuration 3, it is possible to combine conventional smart alternator with the advanced strategy of alternator with mechanical decoupling.

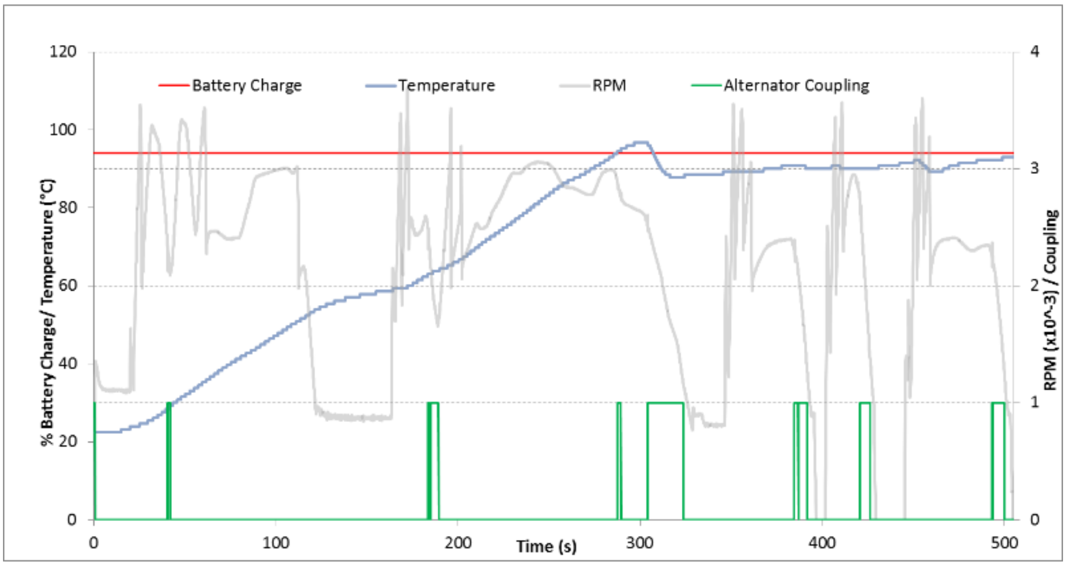

Figure 6 - Alternator decoupling and coupling strategy combined with S&S system representation in function of engine speed (rpm) and operation in the Phase 1 of the urban cycle.

The Figure 7 shows the details of the cut off (alternator coupled), idle and acceleration periods (alternator decoupled). In this figure, the detail of period when the alternator charges the battery during a deceleration at cut off period (coupling in 420 s) is shown. The alternator is decoupled since the vehicle speed of 20 km/h and when the engine speed achieves idle condition (850 rpm), the transmission is disengaged (neutral gear). During the idle period, the fuel injection is reduced because the engine operates without “inertial load” from the alternator, which is decoupled. When the vehicle stops (0 km/h) the internal combustion engine turns off. In that way, it is interesting to emphasize that after engine restarts, the fuel injection is reduced during the acceleration period, since the alternator is decoupled. These conditions represent the greatest advantage of S&S and alternator mechanical decoupling strategies in terms of fuel consumption reduction.

In Phase II of Urban cycle (Figure 8) the strategies combination is possible to verify that despite the various combustion engine restarts events using electric energy (due to the engine starter), the alternator strategies allows the battery state of charge above 85%.

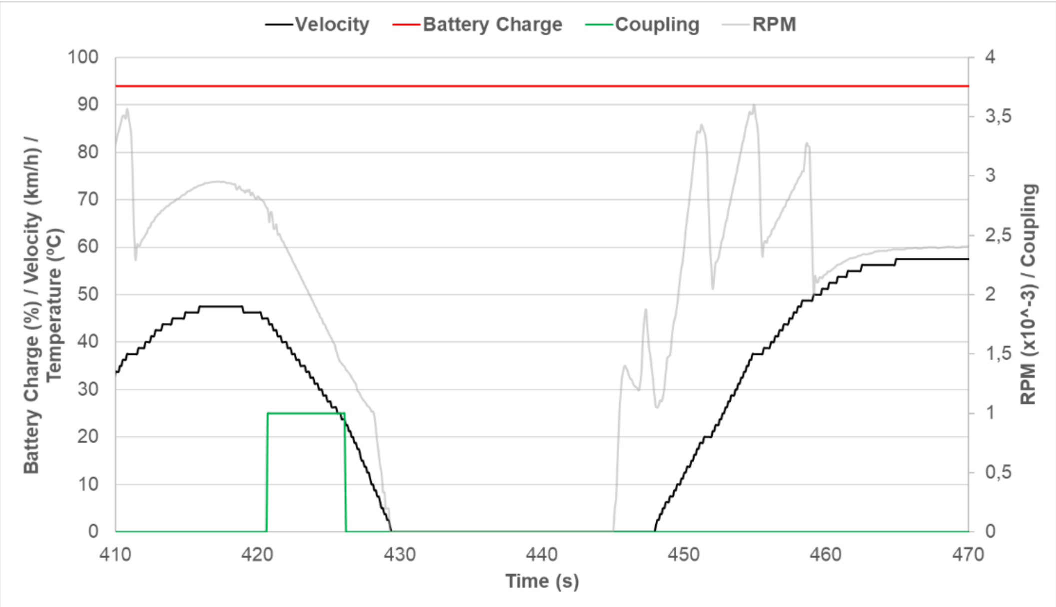

Figure 7 - S&S and alternator decoupling representation in function of engine speed (rpm) and operation in phase 1 of the urban cycle.

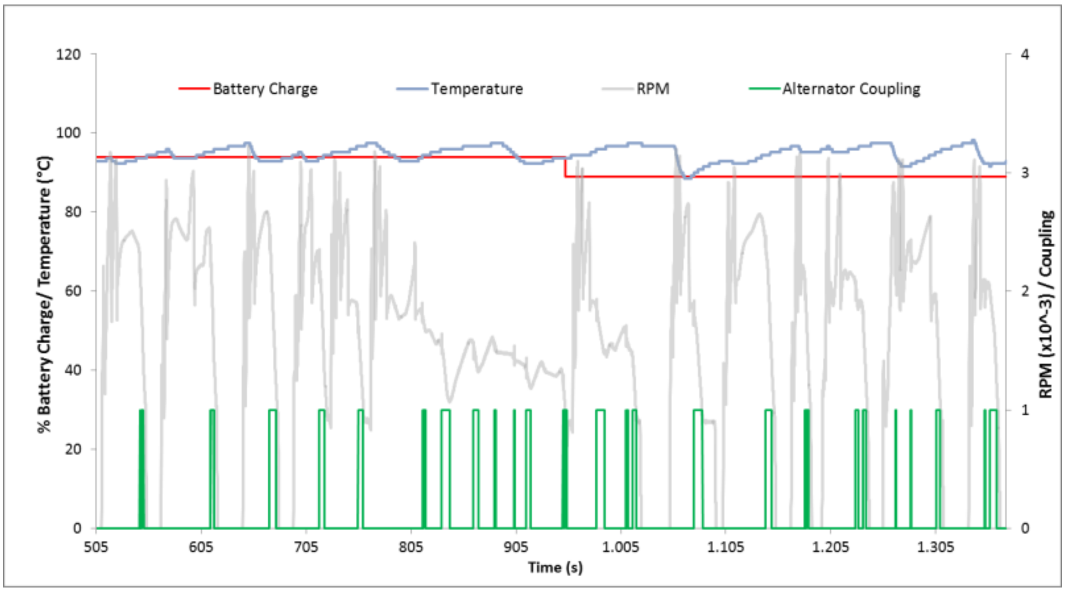

Figure 8 - Combined decoupling and coupling strategy and S&S system representation in function of engine speed (rpm) and operation in phase 2 of the urban cycle.

The Highway cycle is shown in Figure 9, which demonstrates that only the alternator coupling and decoupling strategy was applied, because idle condition for the internal combustion engine to be turned off does not occur.

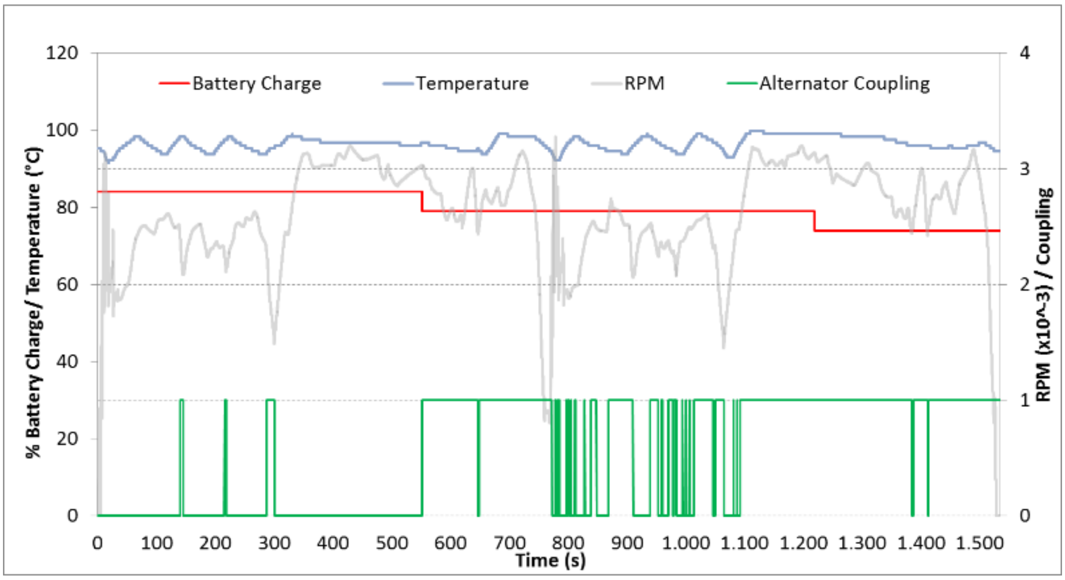

Figure 9 - Combined decoupling and coupling strategy and S&S representation in function of engine speed (rpm) and operation in the highway cycle.

3.4. Comparative of CO_2 emissions and energy consumption

The comparative of results was obtained by the carbon balance method. This method provides the results in l/100km which is converted to MJ/km using the fuel energetic content. The tests were performed with gasoline with 22% of anhydrous ethanol (E22). The comparatives between the configurations are presented as a percentage difference in relation to the baseline configuration. [8] [9]

The CO_2 emissions comparison is illustrated in Figure 10 and shows in the urban cycle that the combination of the S&S and the mechanical and electrical coupling and decoupling configurations of the alternator presented the best result compared to the baseline configuration, with a reduction of 6.51%. Regarding this, the S&S only configuration is 3.85% better than baseline configuration. This 2.66% difference is attributed to the operational strategies of the alternator, relating battery charging and mechanical decoupling. This effect is possible mainly because of the inertial load impact elimination and due to the contribution of the fuel injection reduction in the idle and accelerations periods, combined with the S&S strategy. In Highway cycle there are not idle periods. In that way, the S&S system strategy is not used, so with this configuration it was not possible to obtain CO_2 emission reduction. However, with the alternator strategies combination, a 1.5% CO_2 reduction was achieved.

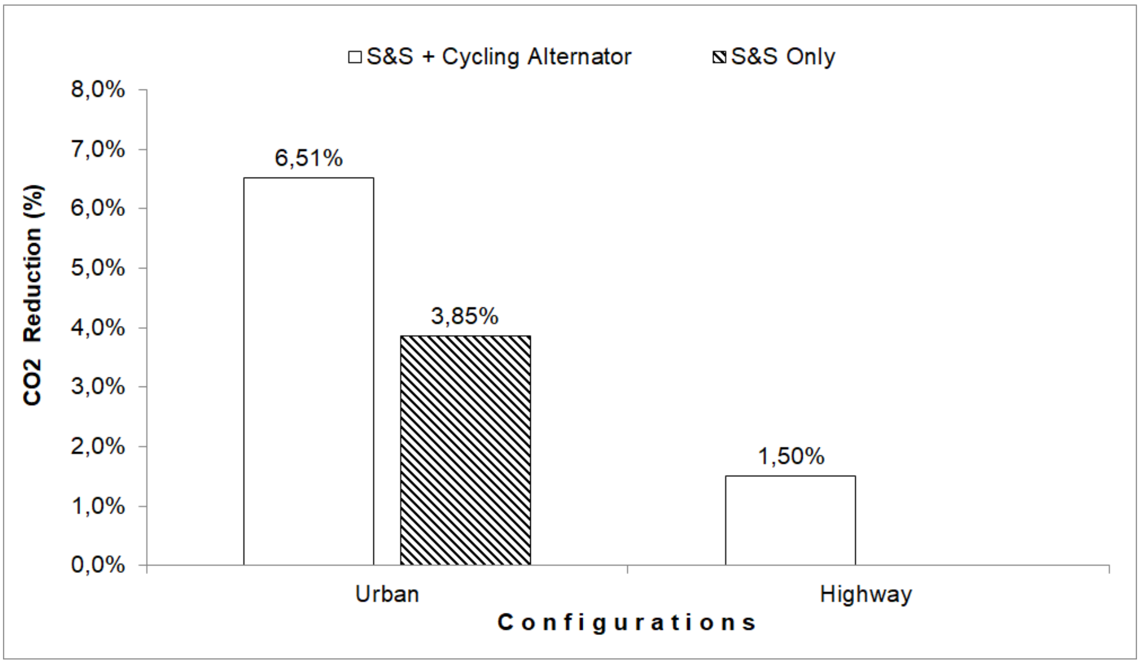

Figure 10 - CO_2 reduction in urban and highway cycles.

The Figure 11 shows the results in terms of reduction of energy consumption (MJ/km) percentage in the three phases of FTP 75 (urban cycle). In Phases I, II and II the S&S combined with the alternator strategies had better results, because even with the cold engine periods, there were decoupling events with reduction of the fuel injection in the periods of idle and acceleration. In Phases II and III the reductions in energy consumption followed the behavior of CO_2 reductions.

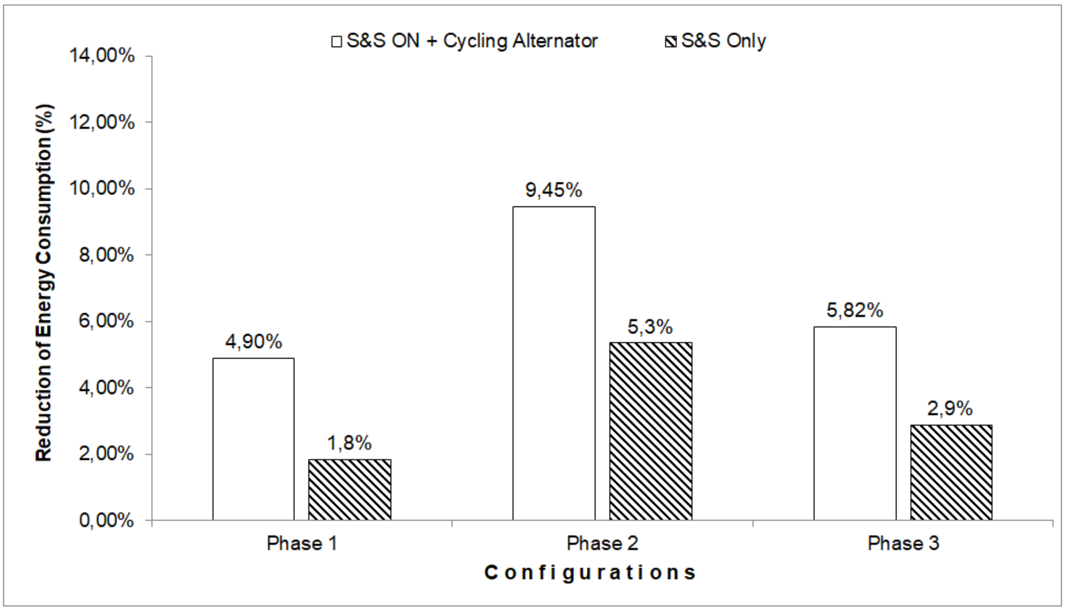

Figure 11 - Energy consumption reduction in Phases 1, 2 and 3 of urban cycle

Figure 12 summarizes the energy consumption reduction results of the Urban, Highway and combined cycles with all the possible technologies configurations of this study. According to the balance carbon method, the energy consumption results were calculated from emissions values in each cycle. Consequently, the reductions of energy consumption followed CO_2 emissions reductions results. The cycling alternator with S&S configuration obtained the greatest energy consumption reduction on urban cycle (7.55%), once there are many opportunities on this type of cycle of decoupling and idle events (consequently internal combustion engine turns off due to the S&S system). In Highway cycle, the S&S combined with alternator strategies provided 0.75% of energy consumption reduction, also only because of the decoupling alternator effects. Then, it was possible to obtain reduction in combined result of 4.91%, while S&S only configuration provides 2.38% reduction.

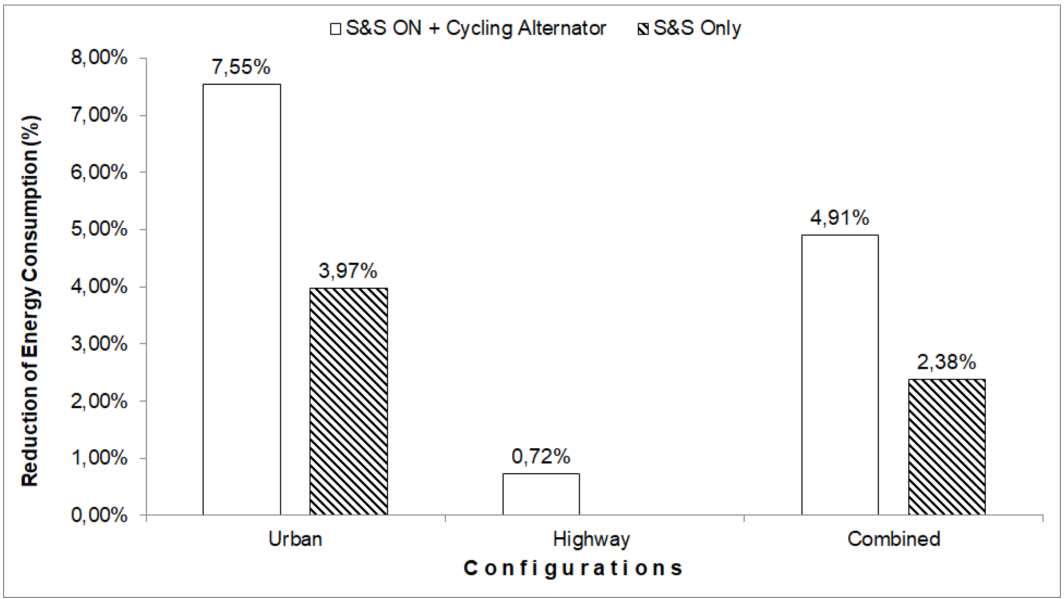

Figure 12 - Energy consumption reduction in urban, highway and combined cycle.

CONCLUSIONS

The S&S combined with the alternator strategies demonstrated that is possible to obtain significant and interesting reductions in CO_2 emission and energy consumption.

In the Urban cycle, the S&S system combined with alternator strategies configuration presented the best result in relation to the baseline configuration, with a reduction of 6.51% and 7.55%, respectively CO_2 and energy consumption. The S&S only configuration is 3.85% better than the baseline configuration.

In the Highway cycle, the effect of S&S system separately didn't provide the reductions related to the CO_2 emission and energy consumption, since there aren't idle periods to turn off the internal combustion engine. On the other hand, the effects of alternator strategies provided significant reductions: 1.5% and 0.72% for CO_2 emissions reduction and energy consumption, respectively.

When the combined results (Urban + Highway cycles) are considered, there is an interesting energy consumption reduction of 4.91%. In that way, the combination of the S&S system with the alternator strategies (mainly because of the mechanical decoupling alternator) is an excellent technological option to apply in automotive industry in order to attend the global legislations regarding energy efficient improvements and CO_2 reductions.

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