26th ABCM International Congress of Mechanical Engineering
November 22-26, 2021. Florianópolis, SC, Brazil

COB-2021-1723
OPTIMIZATION OF THE GEAR RATIO OF A FORMULA SAE CAR THROUGH THE FIREFLY COLONY ALGORITHM

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Abstract. *Formula SAE is a competition that leads students to create and develop their own competition vehicles, being evaluated technical aspects with the justifications for the choice of design and construction, in addition to the dynamic performance of vehicles on the track. This work aims to optimize the gear ratio of the UFU Racing team car by using the integration of a vehicle performance prediction algorithm with the Firefly Colony Algorithm, which is based on meta-heuristics. Three different cases were performed in addition to the reference, changing parameters such as the final ratio and the escalation of the gears, in addition, four different stroke switching times were considered, the objective function was calculated with the weighted average of the lap time in the three tests in which the gait ratio has relevance, Plucked, Autocross and Endure. Only changing the final relationship between the ratchet-chain-crown reduced the meantime by 0.59 % using it in all tests, and 0.95 % if the final relationship is different between the tests. In case there are changes in the escalation of the gears, the average gain becomes 1.57 % which makes great differences for the best teams.*

Keywords: *Formula SAE, Optimization, Gears, Efficiency, Firefly Colony Algorithm.*

1. INTRODUCTION

Formula SAE aims to complement the training of engineering university students based on competition, in which universities seek to build formula-type cars, which are tested in static and dynamic tests (Prorok, 2016). In static, the mode of construction, cost and choice used in the project are evaluated, in addition to safety, and in dynamics, the performance of the vehicle under acceleration, track and fuel consumption is evaluated, (Sae, 2021). The competition has been held by SAE International since 1979 in the United States, but currently there is competition in more than 8 countries, such as Brazil. Formula SAE regulation (Sae, 2021) allowing great freedom in the design of the vehicle, being one of the categories of motorsport that does not restrict the minimum weight. In the combustion category, in which this work fits, it is worth noting that: 4-stroke Otto cycle engines with a maximum of 710 cm^3 are allowed, they must have a cockpit and uncovered wheels, a belt with a minimum of five points and accommodate an adult of at least 1.80 meters.

According to (Seward, 2014), the first gear of a car must have sufficient reduction to remove the car from immobility, but without providing excessive detraction of the drive wheels. The last gear must be dimensioned in such a way that it gets close to the maximum speed of the track without reaching the turning cut. The intermediate relationships are staggered so that they tend to be closer in higher gears, called progression. Furthermore, the author also says that it is common for Formula SAE teams not to use or remove one or more gears from the original gear, due to the circuit not providing high speeds, but the gear ratio must be optimized for the best performance in the races.

For (Yang, 2013), complex problems that involve large numbers of non-linear variables or with multiple objectives may require great computational efforts if treated using traditional methods, such as Pareto diagrams and non-dominant variables even in apparently simple problems. In order to overcome this problem, meta-heuristic algorithms such as the Firefly Colony Algorithm (FCA) show advantages in the optimization of industrial problems. The use of genetic algorithms has already been used to optimize other parameters in Formula SAE, such as the work of (Yang *et al.*, 2017), which seeks to improve the performance of the rear wing, changing angles and positions of two elements, joining computational fluid dynamics with the response surface method.

This work aims to optimize the gear ratio of the UFU Racing Team car, which is composed of students from the Federal University of Uberlândia (UFU), which will compete in the Formula SAE Brazil. The variable time, which is the weighted average lap time of the acceleration and enduro races, will be minimized with the integration of the FCA and lap time prediction algorithm in order to improve the car's performance. From a base model, parameters such as the final reduction of the transmission and the staggering of gears will be changed.

2. METODOLOGY

2.1 Lap time simulator

The algorithm used is a modified version of the one presented by (Barbosa, Tannús and Guarato, 2019) at the 25th Brazilian Congress of Mechanical Engineering. It is written in MatLab® and consists of integration and numerical derivative in each segment of the inserted tracing, which are one-dimensional and with a length chosen by the user, but in this case, 50 mm was used. In the software used, the tracks, car parameters and the torque curve are inserted in a text file.

The parameters used in the car in all simulations are shown in table 1, which are consistent with Formula SAE. In table 2, there are the standard values of the gear ratio or the final reduction of the current, these were used in the last competition of the UFU Racing team, these being the optimized parameters. Engine rotation (Rot_{engine}), in revolutions per minute, is a function of speed (V), primary reduction ($rd_{primary}$), gear reduction (rd_{gear}), transmission reduction (rd_{final}) and tire radius (r_{tire}), according to equation 1. The torque and power curve of all models is shown in figure 1, with the torque obtained by the polynomial interpolation of the engine rotation.

$$Rot_{engine} = \frac{V * rd_{primary} * rd_{gear} * rd_{final} * 60}{2 * \pi * r_{pneu}} \tag{1}$$

Table 1. Default values that will not be modified

Variable	Value
Mass	300 kg
Coefficient of friction	1
Tire radius	0.28 m
Transmission efficiency	0.9
Front area	1 m²
Sustaining coefficient	-2
Drag coefficient	0.9
Specific mass of air	1.2 kg/m³
Traction	Rear
Rear wheel weight fraction	50 %
Center of mass height	0.5 m
Wheelbase	1.5 m
Primary transmission reduction	2.11

Table 2. Default values that will be modified

	Time	Final	1º gear	2º gear	3º gear	4º gear	5º gear	6º gear
Reduction	0.3 s	4.231	2.750	1.938	1.556	1.348	1.208	1.095

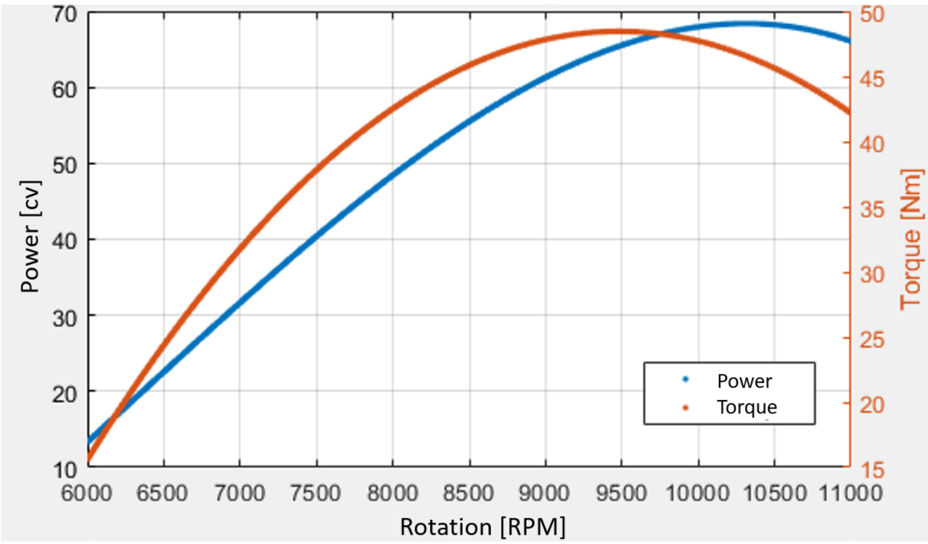

Figure 1. Torque and power curves as a function of rotation, for all models

Three types of tests related to Formula SAE will be studied. The first one is started on a straight track with 75 meters. Despite being on tracks with different layouts and changing every year, the Autocross races, which is only one lap times, and Enduro, endurance race of several laps, will both be represented on the same track for simplification. calls in this work of track evidence. The path used, represented in Figure 2, is consistent with the Formula SAE Brazil and is 690 meters long.

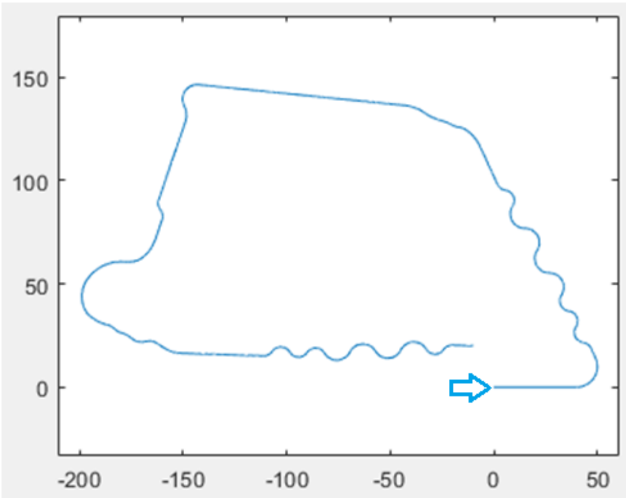

Figure 2. Used track, scaled in meters

In the program, reference values for the standard car were established, which will serve as a reference for optimization. In this way, the standard car covered the drag race in 4.519248 seconds and the race of 67.68372 seconds on the track.

2.2 Firefly Colony Algorithm and Optimized Situations

The Firefly Colony Algorithm (FCA) was developed by (Yang, 2008) in the book Nature-Inspired Metaheuristic Algorithms and used it as an inspiration for firefly mating and bioluminescence. In this algorithm, fireflies are attracted to any other firefly, regardless of gender; the attractiveness is proportional to the glow emitted and decays as the distance between the fireflies increases; the glow emitted by a firefly is determined by its assessment against the target; the attractiveness of a firefly is determined by the intensity of the light emitted; and the determination of the emitted intensity is a function of its evaluation (Yang, 2010).

In a simplified way, the LCA mathematical model is divided into 3 equations, Eq. 2 shows the emitted light intensity I(r), Eq. 3 the attractiveness factor β and Eq. 4 the movement of fireflies x_i^t. Where I0 is the light intensity, γ is the light absorption parameter, β the attractiveness factor, r the distance between the fireflies, βo is the attractiveness for a distance r = 0 and α regularity insertion parameter (Yang, 2010).

$$I(r) = I_o * \exp(\gamma * r^2) \tag{2}$$

$$\beta = \beta o * \exp(-\gamma * r^2) \tag{3}$$

$$x_i^t = x_i^{t-1} + \beta * (x_j^{t-1} - x_i^{t-1}) + \alpha * (rand - 0.5) \tag{4}$$

The performance gain (G_d) in each case will be evaluated according to the Formula SAE regulation, which evaluates the weighted average of each test, with 100 points for the drag race (Par), 125 ready for the Autocross (P_{ac}) and 275 points for the enduro (P_{en}), and the score of each test will be the ratio of the time of the standard car in the drag race (TP_{ar}) and the standard time of the track (TP_{pi}), according to equation 5, and equation 6, which already has the assigned values, leaving only the time of each test. Because the algorithm works with minimization, the objective function value (f) is the negative number of the performance gain, according to equation 6.

$$G_d = \left(\frac{\left(P_{ar} * \frac{TP_{ar}}{T_{ar}} + (P_{ac} + P\_en) * \frac{TP_{pi}}{T_{pi}} \right)}{P_{ar} + P_{ac} + P_{en}} - 1 \right) * 100\ \% \tag{5}$$

$$G_d = \left(\frac{\left(100 * \frac{4.519248}{T_{ar}} + (125 + 275) * \frac{67.68372}{T_{pi}} \right)}{100 + 125 + 275} - 1 \right) * 100\ \% \tag{6}$$

In situations where it is necessary to optimize seven variables, a population of 20 and a number of generations of 1000 were used, in addition to two seeds; when optimizing six variables, 15, 750 and 2 are used, respectively, when optimizing 3, 4 and 5 variables were used 10, 500 and 1 respectively, while when varying 2 or 1 values 10, 150 and 1 are used for number of generations, number of descendants and seeds, respectively. In all cases, α of 0.8; β of 0.7 and γ of 1.

The first case discussed will be optimized only the final reduction, which is constituted by the ratio of the pinion-chain-crown. This is the simplest situation to be built, since it doesn't need to change the relationships inside the standard car gearbox, which would increase the costs and complexity of the project. In this case only one variable will be optimized. In addition, three possibilities of gear shift time will be used in addition to the 0.3 seconds estimated in the current project. Starting at the instantaneous and idealized exchange of 0.0 s, in addition to 0.1 s and 0.2 s.

In the second case studied, it is similar to the first, with the difference that there is a distinction in the relationship between the track tests and the drag test. In this case, two variables will be used to be optimized, the first is the drag ratio, and the second the relationship between the tests (Reep) is defined by according to equation 7, in which Rear is the drag ratio and Repi is the ratio on the track.

$$Re_{ep} = \frac{Re_{pi}}{Re_{ar}} \tag{7}$$

The third case addressed requires greater design and manufacturing complexity, since it is necessary to change components inside the transmission, in this case the final ratio of the drag test will be fixed, and the ratio of each gear will be changed individually, in addition to the relationship between evidences. In this case, the number of gears used may be smaller than the standard, not necessarily being all six gears used, only the best case will be represented in the results. In all cases where the descending order of the gear ratio is not obeyed, the objective function value will be 100, which results in the elimination of the applicant.

3. RESULTS AND DISCUSSIONS

In order to compare the optimized models, reference values for each test were established beforehand. Table 3 shows the results obtained by changing only the gear change time. The gear used at each point on the track is shown in figure 3.

Table 3. Reference case results

Gear change time(s)	0.0	0.1	0.2	0.3
Improvement (%)	1.733025	1.007460	0.573276	0.000000
Acceleration time(s)	4.173631	4.301640	4.414840	4.519248
Track time(s)	67.61878	67.68735	67.59898	67.68372
Number of gears used on the drag track	5	5	5	5
Number of gears used on the mixed track	5	5	5	5
Maximum speed on the drag track (km/h)	105.4615	101.0263	96.5083	96.4870
Maximum speed on mixed track (km/h)	102.3540	100.1312	97.9100	96.5091

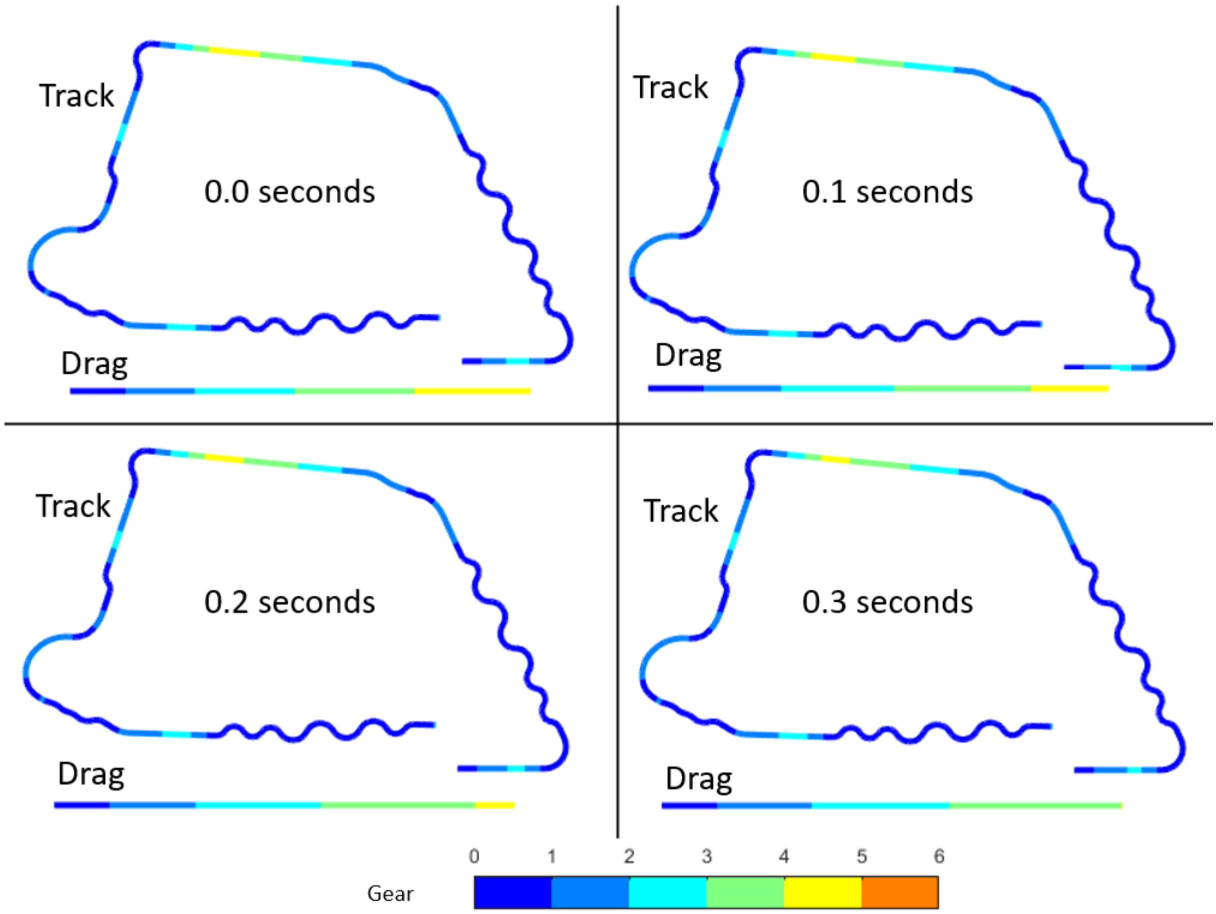

Figure 3. Gears used in the pattern test

In the first optimization test, as shown in table 4, in which only the final ratio is changed and maintained in both tests, as expected, the best time is in the idealized situation of 0.0 second instantaneous gear change, followed by the change 0.1 s; 0.2 sec and 0.3 sec. Figure 4 shows the gear used at each point of the track for the first case, with the track. Another factor to be analyzed is the use of gears, in situations where the time to change is longer, the final ratio tends to be longer, that is, less reduced, using only 3 gears with changes in 0.3 seconds Inverse fact occurs with 0.0 seconds and 0.1 seconds, in which the transmission ratio was shortened, resulting in the use of 6 gears in all tests. It is noteworthy that the maximum speeds in all conditions were higher than the standards, except in the drag test with changes of 0.3 seconds, despite having less time, as the algorithm selected the candidate lost less time in gear changes. Leading at a lower maximum speed, but with a shorter total time weighted.

Table 3. First case results

Gear change time(s)	**0.0**	**0.1**	**0.2**	**0.3**
Improvement (%)	2.532697	1.591407	1.083551	0.587941
Acceleration time(s)	4.152630	4.322473	4.396664	4.462025
Track time(s)	67.04098	67.11248	67.24167	67.40445
Number of gears used on the drag track	6	6	4	3
Number of gears used on the mixed track	6	6	5	3
Final reduction	4.716745	4.880362	4.048911	3.161100
Maximum speed on the drag track (km/h)	105.9066	101.0497	99.2272	95.7310
Maximum speed on mixed track (km/h)	104.1454	100.8478	100.0931	97.7801

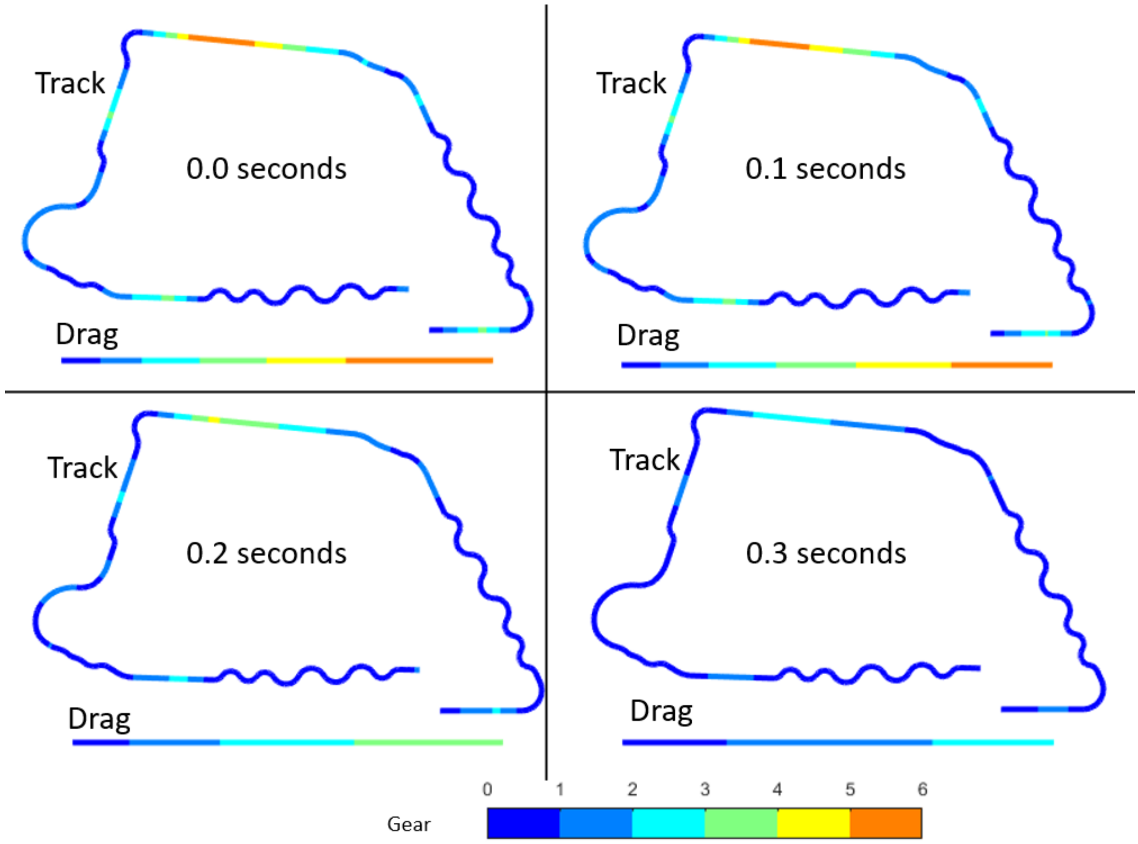

Figure 4. Gears used in the first case

In the second test, shown in table 5, in which the final relationship in both tests is changed, a factor to be analyzed is the greatest reduction in all cases of the track, reaching 1.412123 times more reduced in the change of 0.1 second, in addition, it is important to note that in the track test he used more gears than in drag, a fact also aided by the greater reduction. Another relevant fact is that despite the maximum speed being lower in both the instant change test and in the 0.2 second time track, in relation to the reference, despite the times of all tests were shorter. Figure 5 shows the gear used at each point of the track for the second case.

Table 4. Second case results

Gear change time(s)	**0.0**	**0.1**	**0.2**	**0.3**
Improvement (%)	2.601901	1.840128	1.341584	0.952671
Acceleration time(s)	4.148393	4.273499	4.345283	4.411185
Track time(s)	67.00201	67.10493	67.22919	67.29449
Number of gears used on the drag track	6	4	3	3
Number of gears used on the mixed track	6	5	4	4
Final reduction	4.843308	3.477163	3.469836	3.429729
Final reduction between tests	1.050007	1.412123	1.176610	1.207779
Maximum speed on the drag track (km/h)	103.7836	101.7142	100.4985	97.9012
Maximum speed on mixed track (km/h)	98.8385	100.8849	99.9966	98.5695

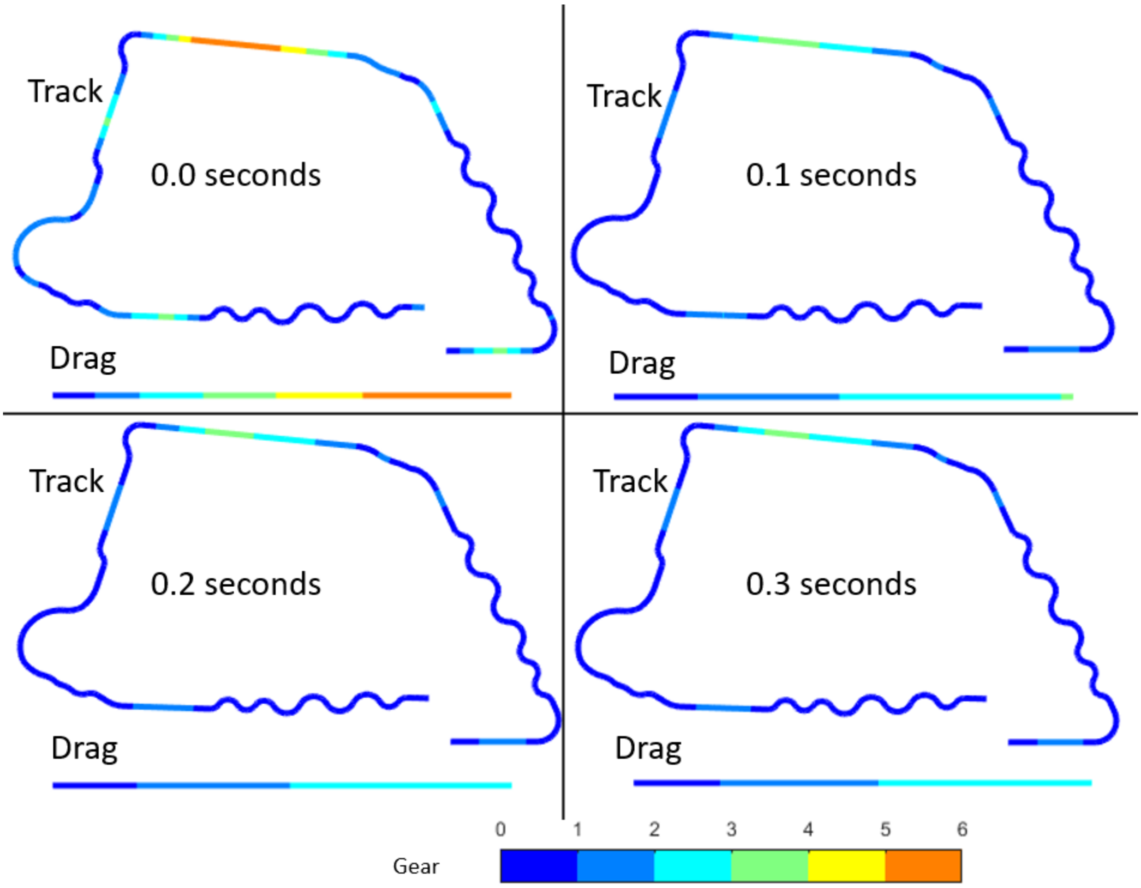

Figure 4. Gears used in the second case

In the third type of optimization, as shown in table 6, in which the ratio of 4.231 in the drag test was maintained, and changing each gear individually in addition to the ratio between the final ratio. Only in instantaneous acceleration were used the 6 gears, and in the other 3 tests only 4 gears were used, the likely reason is the power curve, which is shown in figure 1, in which it has a lower value at low revs, rising from the lower speed from 6000 rpm to the maximum peak close to 10 300 rpm, in this way the instantaneous change allows better distribution in this region. Another interesting factor is that the weighted evaluation system favored the lap time on the track, since all times for this test were shorter than the second case, but in the instantaneous change times and 0.3 seconds, the test time of pluck was greater than the previous case. Furthermore, all top speeds were lower than all the other tests, which shows that the most important factor was the scaling of gears at the corner exits of the track test. It is also important to emphasize that the staggering of gears occurred progressively, tending to be closer in higher gears. Figure 6 shows the gear used at each point of the track for the first case.

Table 5. Third case results

Gear change time(s)	**0.0**	**0.1**	**0.2**	**0.3**
Improvement (%)	3.446698	2.613768	1.986706	1.566960
Acceleration time(s)	4.162041	4.258243	4.343079	4.438540
Track time(s)	66.25088	66.52953	66.70364	66.68076
Number of gears used on the drag track	6	4	4	4
Number of gears used on the mixed track	6	4	4	4
Final reduction	1.100286	1.131609	1.139404	1.016656
1st gear reduction	4.809469	2.228707	2.223748	2.192755
2nd gear reduction	2.633578	1.729152	1.694957	1.568863
3rd gear reduction	2.059842	1.386131	1.417570	1.460749
4th gear reduction	1.641956	1.290528	1.319932	1.364028
5th gear reduction	1.361050	-	-	-
6th gear reduction	1.267020	-	-	-
Maximum speed on the drag track (km/h)	102.6566	100.7868	98.5556	94.3014
Maximum speed on mixed track (km/h)	93.3263	89.0834	86.5162	89.0649

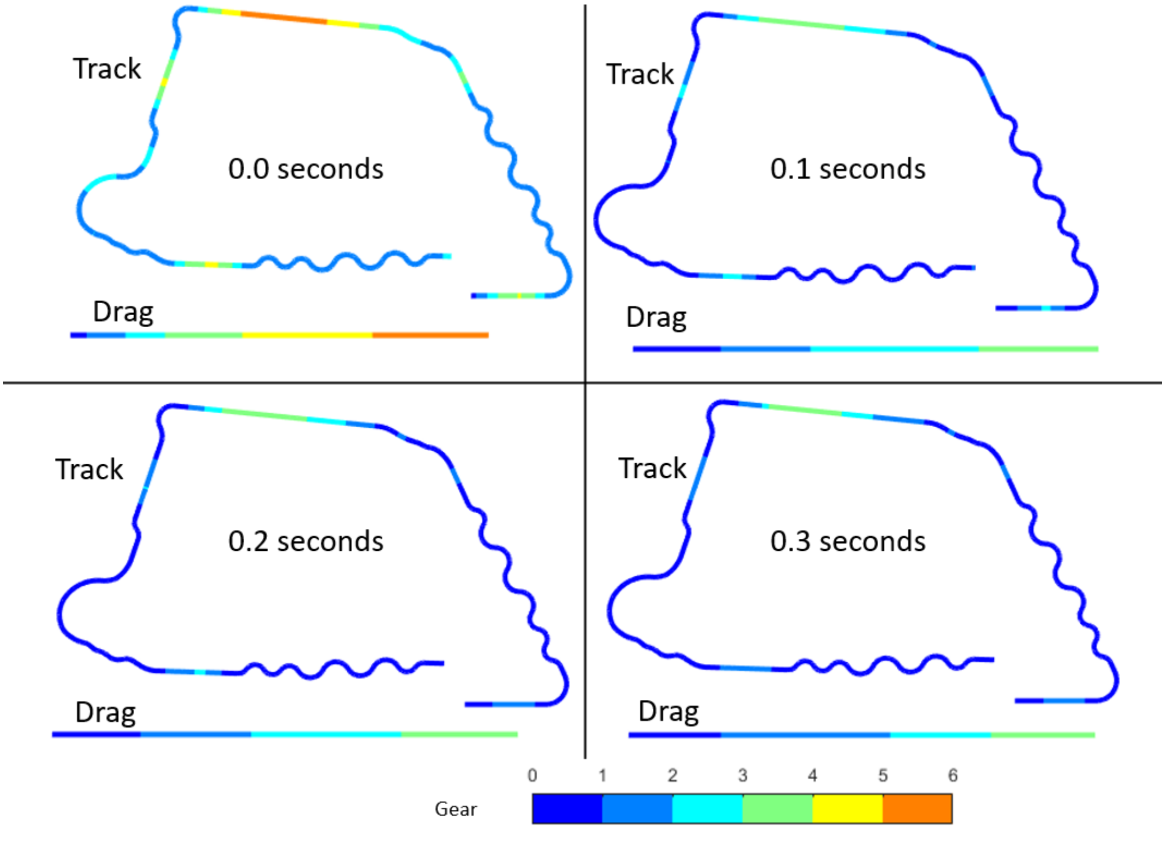

Figure 6. Gears used in the third case

Figure 7 shows how much each gear change time improved in each optimization case, with the zero value of the abscissa axis being the values of the car with change only in the gear time. When performing the averages for each situation, by changing only the differential ratio and keeping it in the two tests, the average gain is 0.62% compared to the standard case, if there are different final relationships between the two tests, the average gain in relation to 0.24% in relation to case one, and 0.86% in relation to the references. When modifying all the gear ratios besides the final reduction, the improvement becomes 0.72% compared to the change only in the ratio and 1.58% compared to the references.

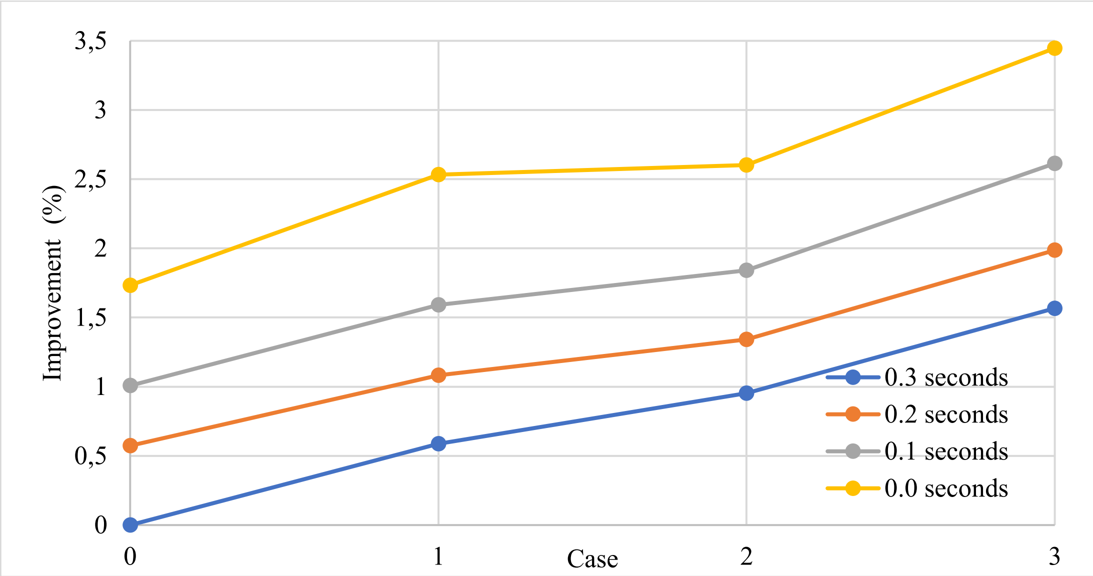

Figure 7. Improvement of each case for all gear shift times

4. CONCLUSIONS

The union of the lap time algorithm with the Firefly Colony Algorithm, managed to predict and optimize the system as expected, because with the increase in the number of variables, it was possible to obtain better values in the objective function, and consequently in the improved model performance. When analyzing only the current exchange time, of 0.3 seconds, changing the final ratio of the ratchet-chain-crown system presents gains of 0.59%, while maintaining the same ratio in all tests, and gains of 0.95 % if the relationship is different between the tests. In addition, if there is greater investment and the possibility of carrying out a more complex project, changing the gears' staggering together with different final relationships between the stages can achieve gains of up to 1.57% in the score, which represents a big difference in value end in only one of the car's systems. This analysis is valid for all other gearshift times used, with little difference in percentage gains. On the other hand, when analyzing the differences between gearshift times in the second case, where the final reductions are different, the improvement if the time passed from 0.3 seconds to the idealized time of 0.0 seconds of 1.94%, but it was for 0.1 seconds, the possible improvement would be 0.89%. Based on the presented ones, it is possible to infer that Formula SAE beginners and intermediate teams should focus primarily on two factors, optimizing the final reduction of the transmission and the search for less time to change gears, leaving changes in the scheduling for top teams, where every little improvement can impact victory.

5. ACKNOWLEDGEMENTS

Thanks to the UFU Racing team for providing project data, in addition to CAPES and CNPQ funding agencies.

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