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# DEVELOPMENT OF AN ALGORITHM FOR PREDICTION OF RACING VEHICLE DYNAMICS AND COMPARISON WITH A COMMERCIAL SOFTWARE

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***Abstract.*** *Due to the need for dynamic vehicle simulation programs, this works proposes the development and validation of a race track prediction algorithm. The code is developed with MatLab®* and it can plot *numerically and graphically comparisons of race track times based on the user inputs of race car and track variables. The validation of the proposed algorithm is carried out through a comparison with OptimumLap® commercial software based on the same input variables. Some improvements in the proposed algorithm are also implemented. Variables that cannot be assessed on OptimumLap® software such as weight distribution, center of mass height and moment of inertia of the wheels and engine are included. The lap time difference between the proposed algorithm and the commercial one is 0.12%. When additional variables included the lap time difference increases to 4.29%.*

***Keywords:*** *Dynamic simulation, Racing vehicles, Formula SAE, race track prediction algorithm.*

## 1. INTRODUCTION

The Formula Racing Team of the Federal University of Uberlandia was created in 2015. This extension project develops a racing car to compete in the Formula SAE event (FSAE International, 2018). Since the foundation of this competition team a software for simulation and validation of the race car project was required (Timings and Cole, 2014). As OptimumLap® software is a versatile and free software it was used in the dynamic simulation of vehicles in order to predict and to compare lap times for different conditions of the car project. This software allows to define characteristics of the cars such as drag and lift coefficient, friction coefficient of the tires, torque curve, gear ratio and weight of the car (Barbosa and Guarato, 2019; Patil et al., 2016, Siegler, 2002). Nevertheless, as OptimumLap® is a commercial software the calculation methods are not well known and there are some limitations on which variables can be tested.

This work aims to create a race track prediction algorithm that is capable of simulating the dynamics of competition cars in race tracks with a larger range of input variables than OptimumLap® commercial software. A comparison between the proposed algorithm and OptimumLap® software using the same variables is carried out for validating it. Additional variables, which are not available on OptimumLap®, are then implemented on the proposed algorithm such as: weight distribution, center of mass height and moment of inertia of the wheels and engine.

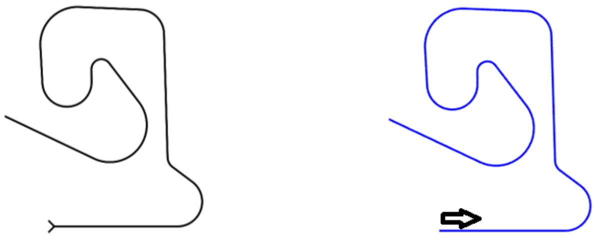
## 2. METHODOLOGY

The proposed prediction algorithm code is developed in MatLab® (Attaway, 2009) through integration and numerical derivative (Asano, 2009). The user can set the track and vehicle's parameters. In the current version, the user can simulate track times with a greater number of variables than the ones available on OptimumLap® software.

### 2.1 Creation of the track

As with OptimumLap® software, in the proposed algorithm the user defines the track in which the model will be simulated by writing a Text File (.txt). This file must contain three columns for each segment of the track. The first column is responsible for defining the segment type, which can be: straight, left curve or right curve, through codes 0, 1, 2, respectively. The second column responsible for the length of each segment, with the measurements in meters. Already the third responsible column is responsible for the radius of curvature, in meters. When the "open circuit" option is selected, the speed on the start line will be zero.

After the stroke is created, it is divided into 0.1 meters segments to allow integration and numerical derivation. In this way, acceleration and speed can be obtained anywhere along the track. In this way, it is possible to obtain acceleration, velocity and displacement. The tracks used are shown in Fig.1, where the first is the design in OptimumLap® and the second in the program created, both with the same length of straight lines and bending radii, having 731 meters.



(a) (b)

Figure 1. Track: (a) OptimumLap®, (b) Created program

### 2.2 Speed in curves

The first step in determining the maximum speed of the car in section is to calculate the maximum speed in curves ($vc_{max}$), which is determined by the radius of curvature (r), coefficient of friction ($coef_{fr}$) and coefficient of lift ($C_l$), gravity (g), air density ($\rho$), mass of the car (m) and frontal area ($a_f$) according to Eq. 1:

$$vc_{\max(i)} = \left( \frac{g}{\frac{1}{cofe_{fr} \cdot r} + \frac{\rho \cdot C_l \cdot a_f}{2m}} \right)^{0,5} \quad (1)$$

### 2.3 Aceleration

After determining the maximum speed in curves, the maximum speed in each track segment is calculated by numerical integration, starting the counter ($i$) on the start line.

The torque curve is found through the polynomial interpolation with degree of interpolation at the user's choice, the points are imported through a text file (.txt), which contains two columns, one related to rotation and another to torque. The power ($H_{eng}$) is found from Eq. 2, relating torque (Tq) to the engine speed ($rot_{eng}$), the Fig. 2 shows the torque and power curve in the analysed car (Brunetti, 1992).

$$H_{eng} = T_q * rot_{eng} \quad (2)$$

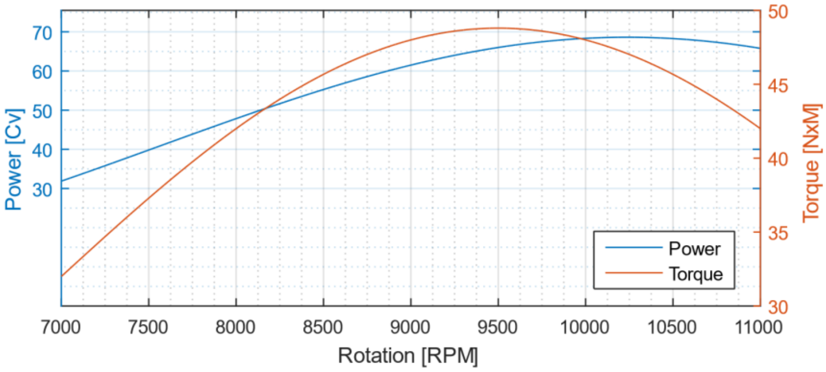



Figure 2: Torque and Power curves

The gear shift is chosen in two distinct cases: the first occurs when the maximum force available on the wheel is smaller in the current gear than the next; the second occurs when the maximum engine speed is reached. Fig. 3 presents the force on the tire as a function of speed, the colour is referring to the gear used.

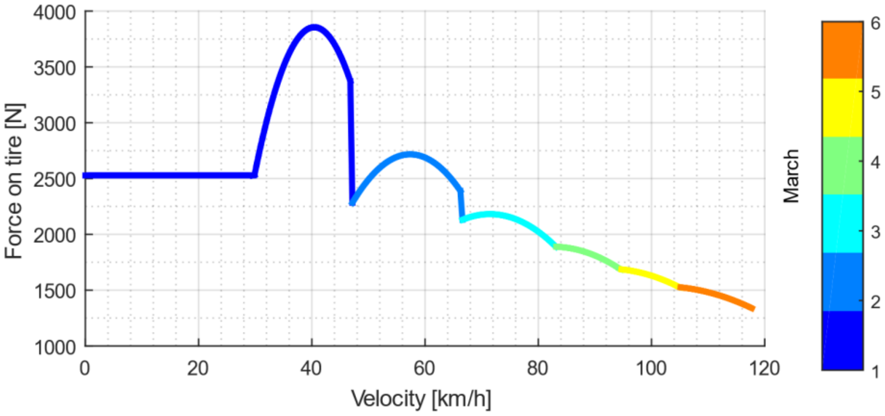



Figure 3: Force on tire vs velocity

It is possible to assess the gear shift time, as the engine power is momentarily cut off and the car will only suffer dissipative forces in the longitudinal until the necessary time runs out. In gear reduction, the same principle is applied. The Fig.4 shows the velocity as a function of time in a straight line, the time bands where the speed decreases is the gear change time. In this case the gear change time is 0.3 seconds.

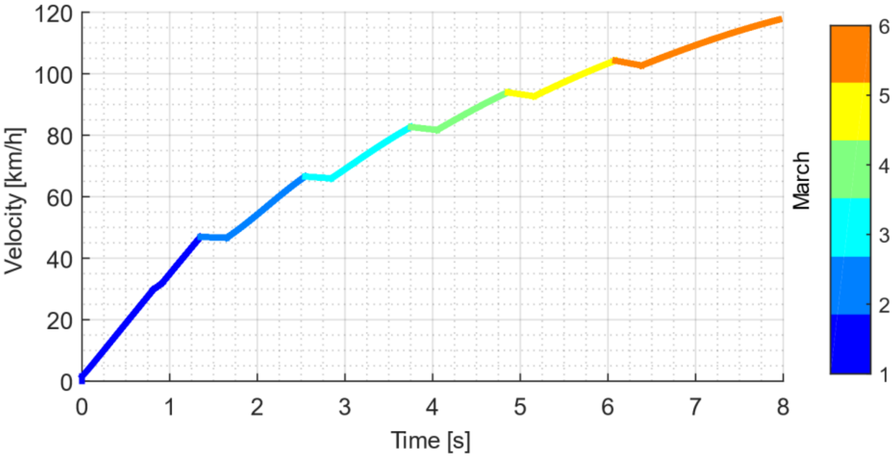



Figure 4: Gear change

The maximum instantaneous acceleration achieved by the engine depends on engine torque ($tq_{eng}$), engine speed (roteng), reduction due to gear ($rd_{gear}$), reduction due to transmission ($rd_{trans}$), engine efficiency ($\eta_{eng}$) and the radius of the tire ($r_{tire}$), and mass (m), moment of inertia of the engine ($I_{eng}$) (Zuquete-Guarato et al., 2012; Guarato et al., 2018) and moment of inertia of the tire ($I_{tire}$), according to Eq. 3. If the motor speed is below than the minimum set by the user, the engine speed will have the same value as the minimum speed.

$$a(i) = \frac{\frac{tq(rot_{eng}) \cdot rd_{gear} \cdot rd_{trans} \cdot \eta_{eng}}{r_{tire}}}{massa + \frac{I_{tire}}{r_{tire}^2} + I_{eng} \cdot \frac{(rd_{trans} \cdot rd_{gear})^2}{r_{tire}^2 \cdot I_{tire}}} - \frac{0.5 \cdot \rho \cdot C_d \cdot a_f \cdot v(i-1)^2}{m} \quad (3)$$

In order to predict wheel slippage, a comparison is made between the acceleration promoted by the engine and the maximum acceleration promoted due to the friction of the tire against the ground ($a_{fr}$), represented by Eq. 4. With the values of maximum accelerations, the lowest value is used, since it is the limiting factor. The maximum acceleration due to friction depends on the distribution of weight on the traction axis (distw), center of mass (Hcg), wheelbase (Lwh), for rear-wheel drive cars. In cars with full wheel drive, the weight distribution value will be set 1 and the height of the center of mass as 0, already in the front-wheel drive models, the height of the center of mass will be negative, in order to correct the generated moment acceleration in the center of mass.

$$a_{fr}(i) = coef_{fr} \cdot g \cdot dist_w + \frac{a(i-1) \cdot H_{cg}}{L_{wb}} - \frac{0.5 \cdot \rho \cdot C_d \cdot a_f \cdot v(i-1)^2}{m} \quad (4)$$

In cases of curves where the initial velocity in the segment is less than the maximum velocity in the curve ($vc_{max}$ (i)), the acceleration (a(i)) is replaced by the maximum longitudinal acceleration in the curve ($a_{lt}$(i)), due to friction cicle, part of the friction is worn with the tangential force and the remainder is available for longitudinal acceleration (Miliken and Miliken, 1995; Lee, 1994). The car is still prone to dissipative forces due to aerodynamic drag (Hucho and Sovran, 1993), according to Eq. 5.

$$a_{lt}(i) = \left(\left(\frac{vc\_max(i)\textasciicircum 2}{r(i)}\right)^2 - \left(\frac{\mathrm{v(i-1)}^2}{\mathrm{r(i)}}\right)^2\right)^{0.5} \cdot \left(dist_w + \frac{a(i-1)\cdot H_{cg}}{L_{wb}}\right) - \frac{\rho \cdot C_d \cdot a_f \cdot v(i-1)^2}{2m} \tag{5}$$

To calculate the time required to traverse each segment (Δt), Eq. 6 is used, depending on the segment length (Δs).

$$\Delta t(i) = \frac{\left(v(i-1)^2 + 2\cdot a(i)\cdot \Delta s\right)^{0.5} - v(i-1)}{a(i)} \tag{6}$$

For the calculation of the final velocity in each segment (v(i)) Eq. 7 is used. If the final velocity of the segment is greater than the maximum speed in curves, the velocity at the end of the segment is replaced by the maximum speed in curves.

$$v(i) = v(i-1) + a(i)\ \cdot\ \Delta t(i) \tag{7}$$

At the end of the calculation of the velocities it is possible to plot the velocity graph according to the position of the track in Fig. 5, note that there is a sudden deceleration, which will be corrected in braking.

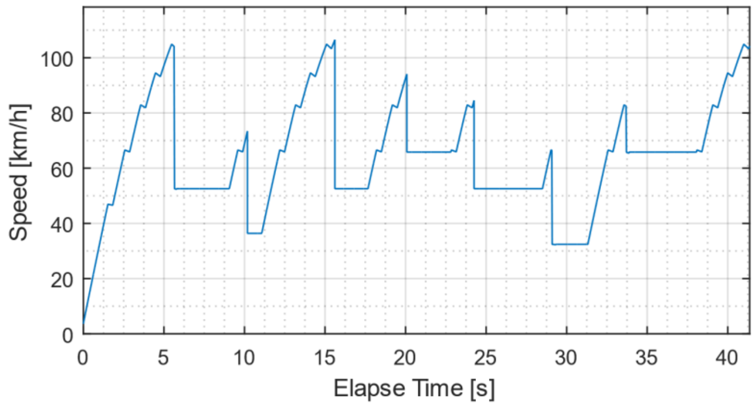



Figure 5. Speed depending on the position of the track.

## 2.4 Braking

In order to correct for abrupt, physically impossible steep drops, the code corrects against acceleration, in which the counter of counter steps $(i)$ instead of starting from the start line, starting from the last segment, until the initial instant. The maximum braking acceleration ($a_{mb}$) is calculated by Eq. 8.

$$a_{mb(i)} = \frac{coef_{at}\cdot(g\cdot m - 0.5\rho \cdot C_l \cdot a_f \cdot v(i)^2) + 0.5\rho \cdot cd \cdot a_f \cdot v(i)^2}{m} \tag{8}$$

If it is on a curve, it is possible to find the maximum braking acceleration ($a_{mbt}(i)$) according to Eq. 9.

$$a_{mbt}(i) = \left(\left(\frac{vc^2_{\max(i)}}{r(i)}\right)^2 - \left(\frac{v^2_{\mathrm{(i)}}}{\mathrm{r(i)}}\right)^2\right)^{0.5} + \frac{\rho \cdot C_d \cdot a_f \cdot v(i)^2}{2m} \tag{9}$$

To calculate the time to go through each braking segment ($\Delta t_b(i)$), Eq. 10 is used.

$$\Delta t_b(i) = \frac{\left(v(i)^2 + 2a_{mb(i)}\cdot \Delta s(i)\right)^{0.5} - v(i)}{a_{mb(i)}} \tag{10}$$

To calculate the initial velocity at each segment point, Eq. 11 is used.

$$v(i-1) = v(i) + af_{\max}(i) \cdot \Delta t_f(i) \tag{11}$$

## 2.5 Graphic interface

A graphical interface is proposed as presented, Fig.6. The so-called "Input" region is where the user defines the value of the variables. The variables type of circuit and traction are defined from the checkbox, since the ratio of gears, torque curve and circuit file are the name of the imported text file. The figures of circuit trace and the torque curve are directly obtained and displayed when the text files are selected. In the region named "Output", the program returns the results. The user can choose which graph to visualize. The "start" button starts the process, the clear button "clear all" response and graphics, and the "close" button closes the program and all graphics.

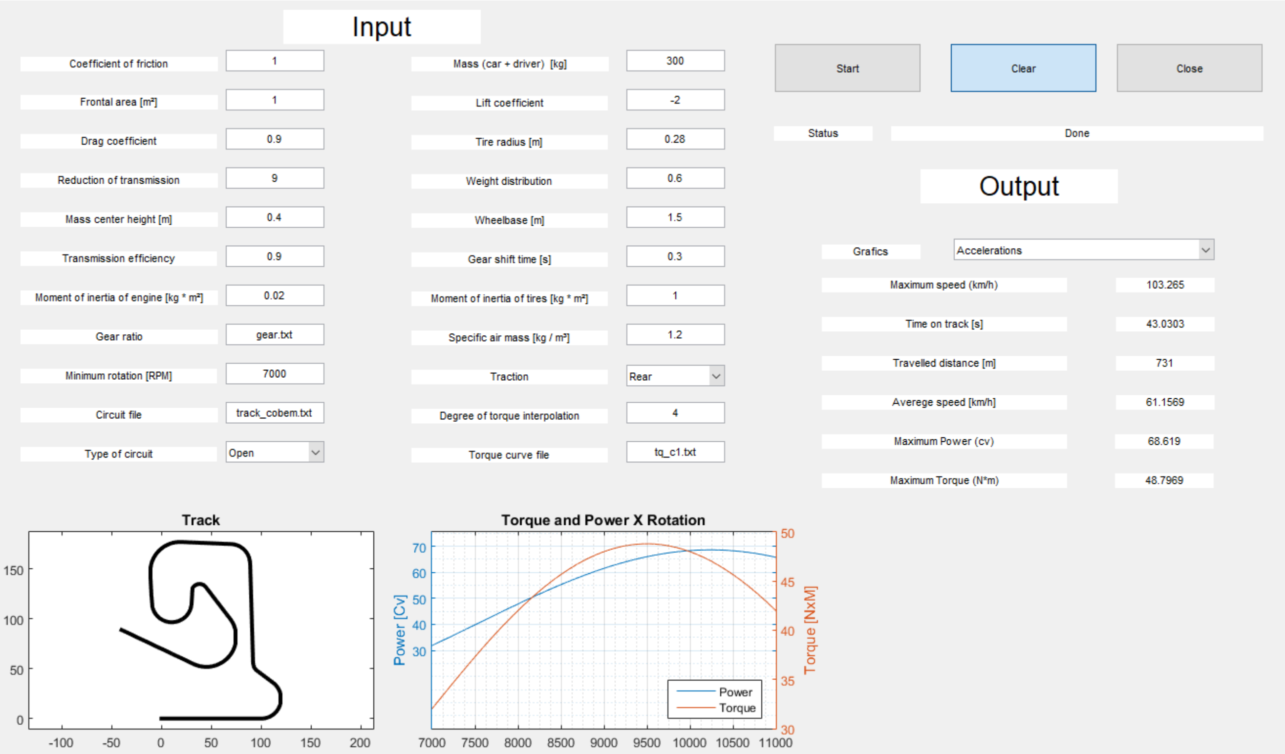



Figure 6. Graphic interface

If the user sets a variable with a value that is physically impossible or out of set standards, the program automatically corrects the input value. An error message appears with the maximum and minimum limits. The corrected value is set as close as possible to the firstly set value into the allowed range. If the corrected value does not fit to the user desire the user can set the input value again. As an example, if one set the coefficient of friction to -0.5, the program corrects the value to 0.5 and warns, "coefficient of friction between 0.5 and 3".

## 2.6 Input variables for validation of the proposed algorithm

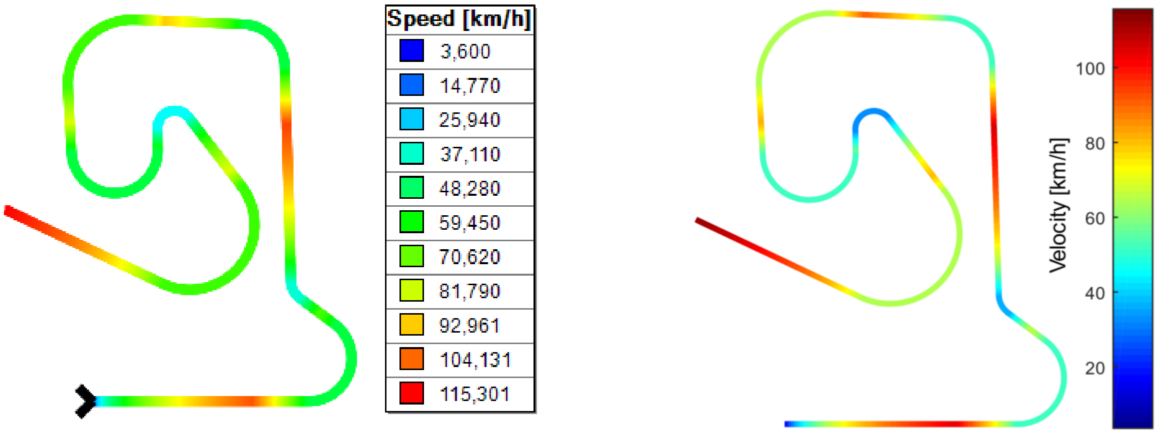
The proposed algorithm is compared to OptimumLap® commercial software using the same track data and car parameters. These parameters are as close as possible to SAE Formula competition and they are presented on Tab.1. The torque curve, previously shown in Fig. 2, and the gear ratio of the 6-speed gearbox are also unchanged. As it is not possible to change the weight distribution on the driven axle, center of mass and wheelbase in the OptimumLap® software, this comparison is used traction on all the wheels, in order to reduce the interference of discrepant variables.

Table 1. Input pparameters for validation.

| Variable | Value |
|---|---|
| Mass (car + driver) | 300 Kg |
| Coefficient of friction | 1 |
| Tire radium | 0.28 |
| Final drive ratio | 9 |
| Transmission efficiency | 0.9 |
| Frontal area | 1 m² |
| Lift coefficient | -2 |
| Drag coefficient | 0.9 |
| Air density | 1.2 Kg/m³ |
| Traction | AWD |

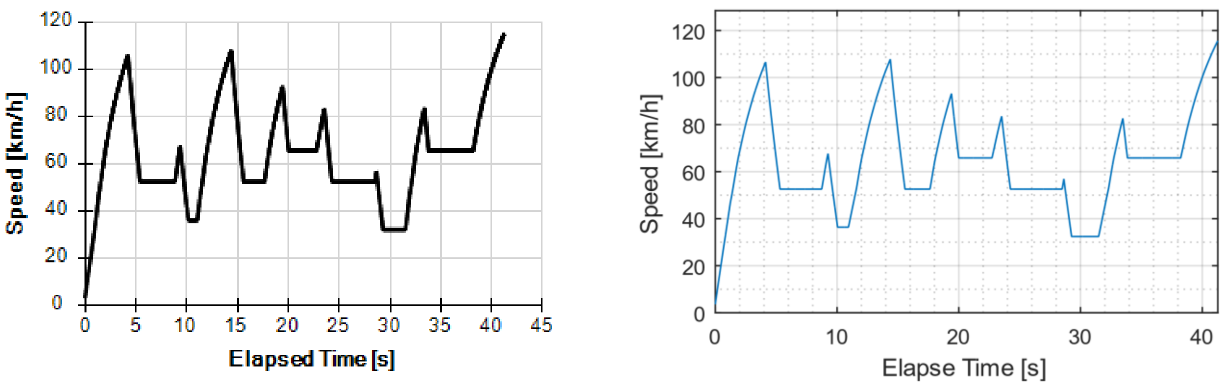
## 3. RESULTS AND DISCUSSION

In terms of lap time and maximum speed, both softwares return similar values. The lap times are, respectively, 41.23 seconds and 41.28 seconds with OptimumLap® and the proposed algorithm. The maximum speeds are 115.30 km/h and 115.62 km/h with OptimumLap® and the proposed algorithm, respectively. The Fig. 7 show the velocity in the track, and Fig. 8 presents the velocities as a function of time with the OptimumLap® and the proposed algorithm, respectively.




(a) (b)

Figure 7. Velocity map: (a) OptimumLap®, (b) the created program.




(a) (b)

Figure 8. Speed *versus* time: (a) OptimumLap®, (b) the created program.

Additional parameters which are not used in Tab. 1 are implemented in the proposed algorithm. Tab. 2 presents the new variables that are not available on OptimumLap®. After the simulation with these additional parameters, the lap time is 43.03 s and the maximum speed is 103.27 Km/h. Fig. 9a shows the speed in the circuit and Fig. 9b shows the speed versus time.

Table 2. Additional parameters on the proposed algorithm.

| Variable | Value |
|---|---|
| Moment of inertia of engine | 0.02 kg·m² |
| Moment of inertia of tires | 1 kg·m² |
| Gear shift time | 0.3 s |
| Traction | Rear |
| Weight distribution (front) | 0.4 |
| Mass center height | 0.4 m |
| Wheelbase | 1.5 m |

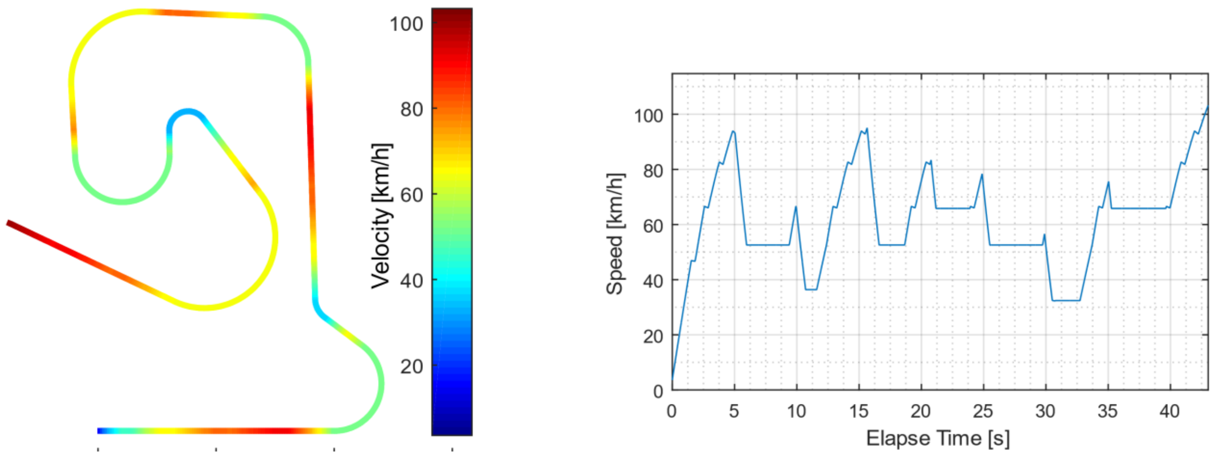



Figure 9: (a) Velocity map in the created program with supplementary variables, (b) Speed *versus* time in the proposed program supplementary variables

Table 3 presents a results comparison between OptimumLap® software and the proposed algorithm without and with addition input variables. When the same parameters are used there is a difference of only 0.12% and 0.28% for lap time and maximum speed. Thus, there is a strong correlation between the proposed algorithm and the commercial software. With additional parameters lap time is 4.37% higher and maximum speed is 10.43% lower in relation to the commercial software. This suggests that the predicted performance with the commercial software is more optimist because less variables are taken into account. Thus, the proposed algorithm leads to more realistic results.

Table 3. Lap time and maximum speed for OptimumLap® and the proposed algorithm without and with additional input variables

| Software | Lap time (s) (% difference) | Maximum speed (Km/h) (% difference) |
|---|---|---|
| OptimumLap® | 41.23 | 115.30 |
| Proposed Algorithm without additional input variables | 41.28 (+0.12%) | 115.62 (+0.28%) |
| Proposed Algorithm with additional input variables | 43.03 (+4.37%) | 103.27 (-10.43%) |

## 4. CONCLUSION

This work proposes a new software for predicting lap time and speeds of race cars based on project and race track parameters. The proposed algorithm validated by comparing it with OptimumLap® commercial software. While using the same input parameters, the proposed algorithm presented a difference of only 0.12% and 0.28% for lap time and maximum speed compared to OptimumLap®. Some additional parameters are also implemented into the proposed algorithm. While these supplementary parameters are taken into account the difference are 4.29% and 10.43% for lap time and maximum speed, respectively. This poorer performance of the race car suggests that the proposed algorithm with using additional parameters indicates more realistic results. Moreover, one advantage of using the proposed code is the possibility of simulating more input parameters than with the commercially available software.

Future work will consider the validation of the proposed algorithm with controlled experimental on track tests.

## 5. ACKNOWLEDGEMENTS

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