International Journal of Scientific & Engineering Research Volume 12, Issue 1, January-2021 115
ISSN 2229-5518

Dynamic modeling and analysis for improving energy-efficient prototype performance

Renan Luís Knabben, Sérgio Junichi Idehara, Helton da Silva Gaspar

Abstract— Contemporary engineering seeks the optimization of processes, new technologies, and the saving of resources, aiming at environmental sustainability. In the field of automotive engineering, universities around the world are working on research and extension projects so that new ideas can emerge in the area. This is the case of the Shell Eco-marathon competition, which aims to design ultra-efficient automotive prototypes. Thus, this work sought to carry out the dynamic modeling and analysis of the use of a suspension system in an ultra-efficient automotive prototype, aiming at the use of automotive technologies for the consequent increase in its energy efficiency. The research was consolidated referencing two virtual models: the original (without a suspension system) and the proposed one (with a suspension system). With numerical simulations, it was possible to carry out vehicle dynamic analysis for both models, such as rollover and energy efficiency. With suspension system parameters, the most significant results were obtained in the rollover analysis, which indicated a reduction of more than 50% in the force acting on the tire in some critical situations. In the case of the energy efficiency, it was evaluated an energy saving of almost 40% in brake situations compared with original configuration, proving the advantage of the use of this mechanism in ultra-efficient prototypes.

Index Terms— Automotive, Design, Shell Eco-marathon, Suspension, Ultra-energy-efficient cars, Vehicle rollover, Vibration

1 INTRODUCTION

Energy efficiency is a topic widely addressed in the industry, as it seeks maximum performance using the least amount of energy possible. The automotive sector follows the same path, as it is based on innovative solutions, such as the development of electric and hybrid vehicles (electric and internal combustion engines acting simultaneously), the use of light materials and the improvement of aerodynamics, for example described by [1] and [2]. Universities and research institutes also work on research projects so that new developments can emerge in the automobile world [3]. Among the various examples, it is possible to mention the energy efficiency prototypes, which use clean energy technologies and have an extremely low consumption for its operation. As one of the main projects, we can mention the energy efficiency teams, which aim to model and develop a virtual design [4], [5], and manufacture automotive prototypes [6] that travel the maximum distance while consuming the least amount of fuel possible. One of the most known competition is Shell Eco-marathon (SEM). In the case of SEM, the prototypes must travel a fixed distance by consuming the least amount of energy.

This is a worldwide energy efficiency competition sponsored by Shell, in which the participants are students from schools and universities in different countries around the world. The teams aim to develop automotive vehicles that achieve the highest possible fuel efficiency [7]. The idea came up in 1939 at Shell's research laboratory, in the United States, when scientists established a friendly bet to find out who could achieve the greatest distance per gallon of fuel. The first official competition took place in France, in 1985, and was attended by thousands of students and scientists from more than 20 European countries. Today, it takes place annually on 4 different continents and has the presence of more than 100 teams per stage [7]. There are two classes of vehicles within the Shell Eco-marathon: prototype and urban concept, which are divided into three categories: electric battery [8], hydrogen fuel cell [9] and internal combustion engine (gasoline, diesel or ethanol).

Energy-efficient prototypes, or also known as ultra-efficient prototypes, Fig 1, are automotive vehicles designed to achieve the maximum possible energy efficiency. That is, travel long distances while consuming less fuel [10]. To achieve such results, some innovations must be applied to prototypes, a feature that makes them different when compared to commercial urban vehicles. As main innovations, it is the use of 3 wheels (two front and one rear) instead of 4, extremely aerodynamic geometry almost without turbulences as described by [11], availability for only one passenger (Fig 2) and the presence of light materials in its structural composition [12]. Sawulski and Ławrynczuk [13] and Omar et al. [14] worked in optimized control strategy related to powertrain low fuel consumption as an automated vehicle engine and motor control, respectively, to achieve an improved performance of this kind of vehicles.

In Shell Eco-marathon competitions, most of the teams choose for projects that contain three wheels. Even so, there are teams that prefer to use four wheels in their vehicles [15]. Such configuration, however, may increase the weight and the rolling resistance since there will be an extra tire in contact with the ground. According to [16], the configuration with three wheels is the most used for providing a series of advantages. As main, already cited aerodynamics, the front and side visibility of the pilot, stability and resistance to overturning. However, despite be-

- Renan L Knabben, Federal University of Santa Catarina, Rua Dona Francisca, 8300, 89219-600, Joinville/SC, Brazil, renan.knabben@grad.ufsc.br
- Sergio J Idehara, Federal University of Santa Catarina, Rua Dona Francisca, 8300, 89219-600, Joinville/SC, Brazil, sergio.idehara@ufsc.br
- Helton S Gaspar, Federal University of Santa Catarina, Rua Dona Francisca, 8300, 89219-600, Joinville/SC, Brazil, helton.s.gaspar@ufsc.br

ISSN 2229-5518

ing very competent, their embedded technology is relatively simple, a condition that may compromise the handling, comfort and safety of its users [17]. The use of a light structure, like in the chassis design, may decrease its stiffness and strength [18]. Kral et al. [19], for instance, discuss that a higher structure stiffness is needed to achieve a correct geometry of the steering system when cornering, which can increase the overall weight. Some solutions are studied to improve the vehicle safety, as the approach made in [20] and [21]. The authors developed an Advanced Driver Assistance Systems to improve on driver and vehicle safety predicting possible collision situations. These mechanisms may avoid more serious injuries on the driver as found by [22].

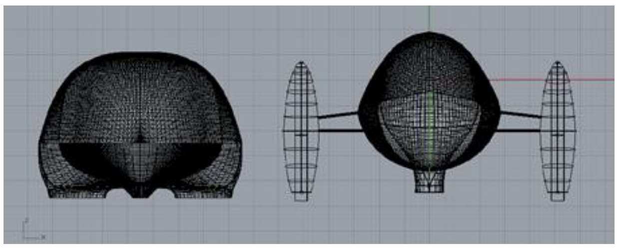

Fig. 1. Frontal view of the ultra-efficient prototype design (Federal University of Santa Catarina, Eficem).

Fig. 2. One-person ultra-efficient prototype (Federal University of Santa Catarina, Eficem).

Then, seeking a development of a very light ultra-efficient prototypes, most teams choose to design vehicles that are too simple, avoiding the use of common components found in commercial cars. However, given that the main objective of the project is to achieve the maximum energy efficiency, the performance of the vehicle should be analyzed regardless of its weight. Thus, the insertion of certain mechanical components in the prototype, such as a suspension system, can contribute significantly to its final efficiency despite the weight increasing. Carlsen and Oma [23] built a vehicle prototype for Shell Eco-Marathon using suspension system that may improve the control of camber and caster angles related to the vehicle dynamics.

The suspension is one of the main sets of an automotive vehicle, it has the role of ensuring tire/ track contact, providing comfort to users and also safety in the curve driving at higher speeds, thus ensuring more stability. As defined by [24], the suspension is responsible for meeting the driveability and comfort required for a large number of conditions, such as loaded/ unloaded vehicle, acceleration/ braking, straight line/ curves and regular/ irregular streets. Another primary function of the suspension system, according to [25], is its direct contribution to the performance of the vehicle on the road. In curve, relieving the efforts from the lateral dynamics and allowing its execution at higher speeds, as well as in a straight line, generating greater stability and control of the car in the face of efforts caused by accelerations and more intense braking (longitudinal dynamics).

In the case of energy efficiency prototypes, the focus on the suspension system is not limited to relieving the excitations arising from the irregularities of the road, but rather maximizing its performance in terms of handling, especially in cornering situations, promoting more stability and avoiding rollover to the vehicle, [26], where the driver can work at higher speeds in such conditions. Therefore, it is necessary to adopt a set of values of stiffness and damping according to the vehicle dynamics, seeking a gain in efficiency and better control of the prototype by the pilot. The Fig 3 show a sequence of snapshots taken of an accident with the EFICEM team prototype during SEM 2019. They exemplify the risk of suspension system absence.

Fig. 3. Illustration of a rollover case during cornering movement.

Thus, in this work a theoretical studies and discussions of the suspension allocation in the prototype is described, regards to less reduction of vehicle velocity in cornering maneuvers, based on the velocity limit to avoid the rollover [27], and improve the general vehicle energy efficiency.

2 Material and Methods

The theoretical considerations and bases used to develop the mathematical model will be detailed. In order to evaluate the energy efficiency provided by the suspension system, numerical simulations of the vehicle dynamics are performed.

2.1 Mathematical modeling

The study of the movement of a vehicle initiates with its dynamic modeling, which involves its degrees of freedom (DOF) and the determination of its coordinate system. The dynamic equilibrium equations that govern the system's response can be expressed in the matrix form, according to following equation:

$$[M]\{\ddot{z}(t)\} + [C]\{\dot{z}(t)\} + [K]\{z(t)\} = \{F(t)\} \quad (1)$$

It contains mass $[M]$, damping $[C]$ and stiffness $[K]$ parameters written in the form of matrices, along with vectors of acceleration $\{\ddot{z}(t)\}$, velocity $\{\dot{z}(t)\}$, displacement $\{z(t)\}$ and force $\{F(t)\}$, which are in the time domain. For ultra-efficient automotive prototypes, which have three wheels (two at the front and one at the rear), two different models will be compared: the first one (Fig 4) represents the current configuration of ultra-efficient prototype, without a suspension system (3 DOF model). The second one, Fig 5, will have a suspension set on its front wheels (5 DOF model), enabling in-depth analysis of its dynamics depending on the final efficiency.

2.2 Three DOF Model

The model degree of freedom corresponds to the vertical displacement of the mass in z, called bounce (z_s), and its rotations in x and y, called roll (ϕ) and pitch (θ), respectively. The dynamic equation is:

$$m_s.\ddot{z}_s = -k_t.z_{s1} - k_t.z_{s2} - k_t.z_s - c_{zs}.\dot{z}_s \quad (2)$$

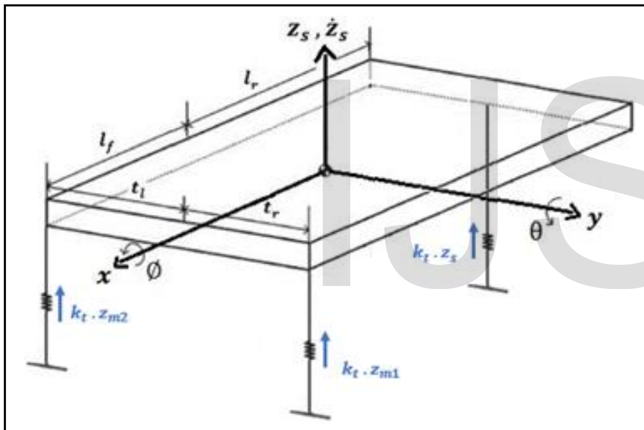

Fig 4. Model of 3 Degrees of Freedom.

The variables m_s and $\ddot{z}_s$ represent the value of the sprung mass of the prototype and its acceleration, respectively. k_t is equivalent to the tire stiffness constant. The product $c_{zs}.\dot{z}_s$ represents the mechanical friction present in the displacement of the suspended mass. The variables z_{s1} and z_{s2} correspond to the displacement in z of the suspended mass in the front left and right ends of the prototype, respectively, which are written using the equations:

$$z_{s1} = z_s - l_f.tan\,(\theta) + \frac{1}{2}.t_b.tan(\phi) \quad (3)$$

$$z_{s2} = zs - l_f.tan\,(\theta) - \frac{1}{2}.t_b.tan(\phi) \quad (4)$$

The l_f symbol is equivalent to the longitudinal distance from the front of the prototype to its center of gravity. t_b denotes the width of the gauge (t_r + t_l). Other two equations in the model come from the x and y rotations of the suspended mass, resulting in (5) and (6).

$$I_x.\ddot{\phi} = \frac{1}{2}.t_b.(z_{s2}.k_t - z_{s1}.k_t) - c_{tx}.\dot{\phi} \quad (5)$$

$$I_y.\ddot{\theta} = -k_t.l_r.tan^2(\theta) + 2.k_t.l_f.tan^2(\theta) - c_{ty}.\dot{\theta} \quad (6)$$

The variables I_x and I_y correspond to the moments of inertia of the axes of longitudinal and transversal rotation, respectively. In turn, l_r represents the longitudinal distance from the center of gravity to the rear axle of the prototype. The products $c_{tx}.\dot{\phi}$ and $c_{ty}.\dot{\theta}$ represent the mechanical friction present in the x and y rotations, in sequence.

2.3 Five DOF Model

This model has five degrees of freedom, which are:

1. bounce (z_s),
2. roll (ϕ),
3. pitch (θ),
4. vertical displacement of the sprung mass and vertical displacement of the unsprung mass of the left front wheel (z_{m_1}),
5. and right front wheel (z_{m_2}).

The equation of the model is

$$\begin{aligned} m_s.\ddot{z}_s = &-k_1.(z_{s1} - z_{m1}) - c_1.(\dot{z}_{s1} - \dot{z}_{m1}) \\ &- k_2.(z_{s2} - z_{m2}) - c_2.(\dot{z}_{s2} - \dot{z}_{m2}) \\ &- k_t.z_s - c_{zs}.\dot{z}_s \end{aligned} \quad (7)$$

The variables k_1 and k_2 are equivalent to the stiffness constants of the suspension 1 and 2, in that order. Similarly, the constants c_1 and c_2 refer to the damping of suspension 1 and 2.

The equations of displacements at the front left (z_{s1}) and right (z_{s2}) ends refer to (3) and (4), already shown in the previous model. In turn, the velocity equations are:

$$\dot{z}_{s1} = \dot{z}s - l_f.\dot{\theta}(\theta) + \frac{1}{2}.t_b.\dot{\phi}.sec^2(\phi) \quad (8)$$

$$\dot{z}_{s2} = \dot{z}s - l_f.\dot{\theta}(\theta) - \frac{1}{2}.t_b.\dot{\phi}.sec^2(\phi) \quad (9)$$

Analogously the unsprung mass equations are

$$m_1.\ddot{z}_{m1} = k_1.(z_{s1} - z_{m1}) + c_1.(\dot{z}_{s1} - \dot{z}_{m1}) - k_t.z_{m1} \quad (10)$$

$$m_2.\ddot{z}_{m2} = k_2.(z_{s2} - z_{m2}) + c_2.(\dot{z}_{s2} - \dot{z}_{m2}) - k_t.z_{m2} \quad (11)$$

The variables m_1 and m_2 are equivalent to the values of the unsprung masses. In turn, $\ddot{z}_{m_1}$ and $\ddot{z}_{m2}$ correspond to their accelerations. The last two equations of the model are obtained through the x and y rotations of the sprung mass:

$$I_x.\ddot{\phi} \;=\; 1/2.t_b.[\,k_2.(z_{s2} - z_{m2}) \;+\; c_2.(\dot{z}_{s2} \;-\; \dot{z}_{m2}) \\ -\; k_1.(z_{s1} - z_{m1}) -\; c_1.(\dot{z}_{s1} - \dot{z}_{m1})] \\ -\,c_{tx}.\dot{\phi} \tag{12}$$

$$I_y.\ddot{\theta} = \;[\,k_1.(z_{s1} - z_{m1}) + c_1.(\dot{z}_{s1} - \dot{z}_{m1}) \\ +\; k_2.(z_{s2} - z_{m2}) \\ +\; c_2.(\dot{z}_{s2} - \;\dot{z}_{m2})\,]\,.\,l_r \\ -\; k_t.{l_f}^2.tan(\theta) \;-c_{ty}.\dot{\theta} \tag{13}$$

Thus, with the definition of all the physical equations of the proposed model, it is possible to determine the complete movement of the vehicle by the numerical differential equation solution.

2.4 Vehicle dynamics

An extremely important factor for any energy efficient vehicle is its performance in curves, because, due to the limited geometry and stability, it is subject to overturns, mainly in curves with small radii that require lower speeds to be performed. Initially, it is assumed that the vehicle is in uniform circular motion, with a given speed V and radius R. In these circumstances there is a force (F_{cp}) that keeps the vehicle on its path:

$$F_{cp} = m\,.\frac{V^2}{R} \tag{14}$$

In the non-inertial frame of reference fixed on the vehicle, a fictitious force acts over its CG towards the centrifugal direction, with the same magnitude of the centripetal force. As consequence of the resulting force, a positive resultant moment is generated (M_r), which tends to make the prototype overturn. It is calculated by multiplying the resulting force by the distance between the center of gravity and the floor, h_{cg}, [28].

$$M_r = m\,.\frac{V^2}{R}\,.h_{cg} \tag{15}$$

In the situation shown in Fig 6, it is assumed that the rollover starts when the vehicle's internal wheel is on the verge of losing contact with the ground. Therefore, in order to perform the rollover-related analyzes, the equations corresponding to the normal forces of the prototype must be determined. Initially, the situation of static equilibrium is assumed. Thus, the prototype (3 and 5 DOF models) is subject to the normal forces N_1, N_2 e N_3 (one for each wheel), which are equivalent to the weight force (P), found multiplying the total mass of the prototype (M_t) by the gravitational constant (g). Applying the sum of forces in z and the sum of moments in x and y, the following equations are found:

$$N_1 = \frac{M_t.g}{2} - \frac{M_t.g.l_f}{2.(l_r + l_f)} \tag{16}$$

$$N_2 = \frac{M_t.g}{2} - \frac{M_t.g.l_f}{2.(l_r + l_f)} \tag{17}$$

$$N_3 = \frac{M_t.g.l_f}{(l_r + l_f)} \tag{18}$$

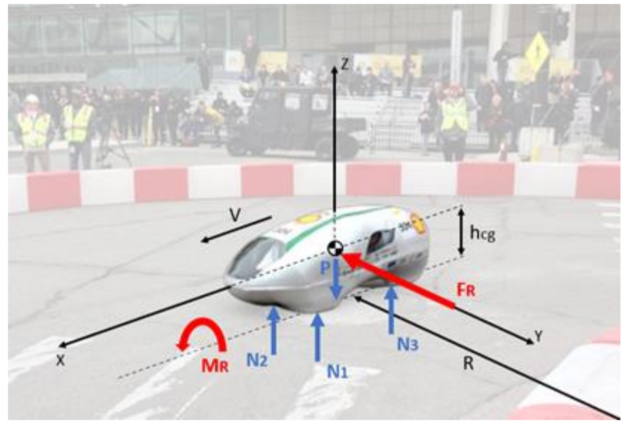

Fig. 6. Lateral Dynamic Analysis of an Ultra-efficient Prototype.

In dynamic condition, the magnitude of these normal forces of the prototype (N_1 or N_2, depending on the direction of the curve) is compared with the product of the displacement of the unsprung mass (z_{m1} or z_{m2}) by the tire stiffness (k_t). If the magnitude of the terms $z_{m1}.k_t$ or $z_{m2}.k_t$ exceeds the normal force (N_1 or N_2), respectively, it is assumed that the tire starts to lose contact with the track, where it is a rollover possible situation.

2.4 Numerical simulation setup

The simulations, in Matlab environment, are performed by using the real conditions of the Shell Eco-marathon Americas circuit (Sonnoma Raceway, adapted), Fig. 6. The vehicle velocity will be considered constant in the track. The virtual model of an ultra-efficient automotive prototype, Fig 8, was based to obtain the parameters of the vehicle, where the data is presented in the Table 1.

3 Results

The vehicle's rollover begins when its wheel inside the curve is on the verge of losing contact with the ground. Therefore, the magnitude of the normal force of the wheel is compared with the term $z_{m1}.k_t$ or $z_{m2}.k_t$ (depending on the direction of the curve), where the prior are shown in red lines and the last one in blue line in the plots of Fig 9 and Fig 10. The results, for circuit loop with a constant speed of 7 m/s, for the 3 DOF model can be seen in Fig 9 and Fig 10. Analyzing the graphics, at the points where the blue line exceeds the red line, the tire loses contact with the ground, therefore, there are great chances of overturning. As the model under analysis does not have parameters for damping and stiffness, it is noted that at certain points the tire force was higher than the normal force, generating critical riding situations.
(8)

TABLE 1
PARAMETERS OF AN ULTRA-EFFICIENT VIRTUAL MODEL PROTOTYPE.

Parameter	Value
Distance between front axle and CG (l_f)	0.668 m
Distance between rear axle and CG (l_r)	0.849 m
Gauge length (t_b)	0.598 m
Suspended mass (m_s)	80.088 kg
Left unsprung mass (m_1)	2.830 kg
Right unsprung mass (m_2)	2.830 kg
Total prototype mass with driver (M_t)	85.676 kg
Longitudinal moment of inertia (I_x)	92.109 kg.m²
Transverse moment of inertia (I_y)	79.202 kg.m²
Distance between CG and track (h_{cg})	0.608 m
Spring stiffness 1 (k_1)	11759.55 N/m
Damping constant 1 (c_1)	1554 N.s/m
Spring stiffness 2 (k_2)	11759.55 N/m
Damping constant 2 (c_2)	1554 N.s/m
Tire stiffness (k_t)	1175955.50 N/m

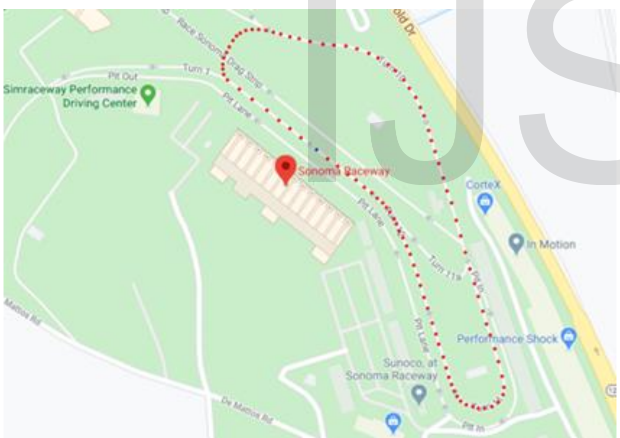

Fig 7. Computational Mapping of the Track.

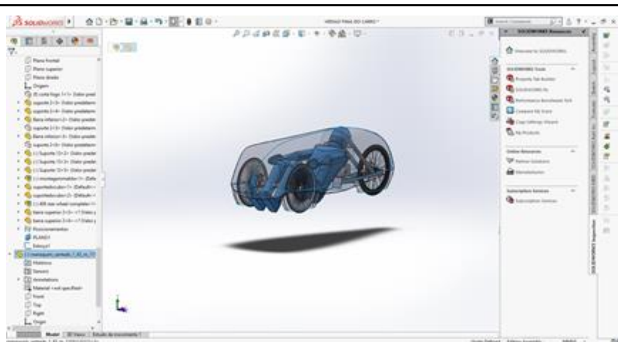
Fig 8. Ultra-Efficient Prototype CAD Model with Driver.

At instant t = 23s, the left wheel loses its normal force at a value of 933N (Fig 9), while the normal for the static condition is 235N (red line). This is equivalent to a value close to four times the allowed limit for the prototype to be able to execute the curve without losing the contact of the tire with the ground. The situation was even more worrying in the analyzes of the prototype's right wheel (Fig 10), as in t = 111s, when the wheel loses its normal force to a maximum value of 1,024N.

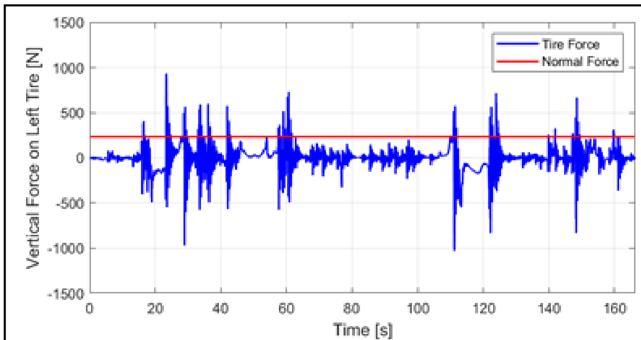

Fig 9. Left Wheel Rollover Analysis of the 3 Degrees of Freedom Model.

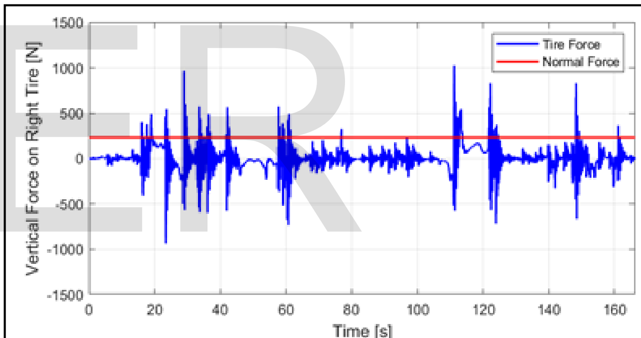

Fig 10. Right Wheel Rollover Analysis of the 3 Degrees of Freedom Model.

Analogously to the previous case, the possibility of overturning for the 5 DOF model with suspension system throughout the circuit was evaluated. The graphics of tire force versus normal force are shown in Fig 11 and Fig 12. As in the previous case, the 5 DOF model also provides critical riding situations. Operating under the same initial conditions previously mentioned, there are times when the wheel would lose contact with the ground, which can result in eventual overturns. However, it is noted that the intensity reached by the tire force was reduced considerably when compared to the 3 DOF model. This can be explained by the insertion of a suspension system in the front wheels of the prototype, which has the purpose of reducing the magnitude of this force. In the analysis of the left wheel (z_{m1}), which can be seen in Fig 11, the magnitude of 283N was obtained as the most critical value of the force applied to the tire, at the time of approximately t = 29s. Regarding the right wheel (z_{m2}), shown in Fig 12, the maximum intensity of the force reached on the tire was 478N, at time t = 113s.

ISSN 2229-5518

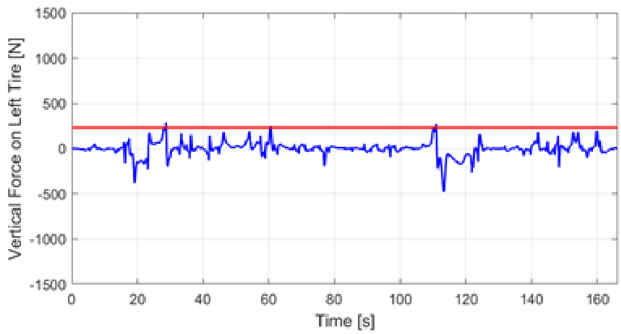

Fig 11. Left Wheel Rollover Analysis of the 5 Degrees of Freedom Model.

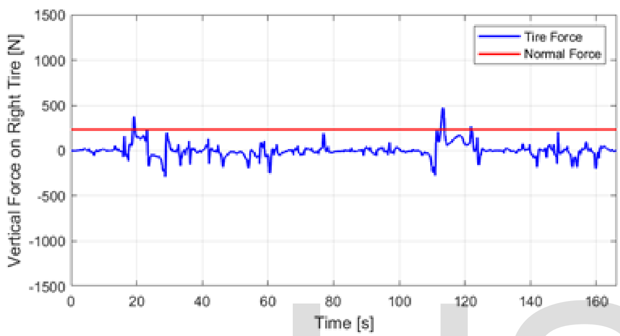

Fig 12. Right Wheel Rollover Analysis of the 5 Degrees of Freedom Model.

It is important to emphasize that the main gain of the prototype with the inclusion of a front suspension system consists in the decrease of the magnitude of the force applied on the tire, which was reduced by more than 50% in the critical sections of the track when compared to the previous model. This allows the prototype to drive the curves faster, without the need for drastic braking, which implies a lower speed resumption at the exit of the curve and, consequently, makes the vehicle more efficient.

To estimate the energy savings related to the addition of a front suspension system in the prototype, the energy expenditure of the braking performed at the entrance of each curve is calculated for both models. Initially, the Shell Eco-marathon circuit is segmented into four main curves, which are shown in the figure below.

In order to calculate the dissipated energy as a function of the braking on each stretch indicated in Fig 13, the kinetic energy variation equation is used:

$$E_k = \frac{M_t \, . \, (V_r{}^2 - V_n{}^2)}{2} \tag{19}$$

SEM regulations require vehicles to complete the 8 laps of the competition in a maximum of 24 minutes. Thus, based on the total length of the circuit (1,164 m), it is calculated that the minimum average speed to be adopted by the prototype is approximately 7 m/s. Therefore, this will be the reference speed (V_r). Through the simulations, it is estimated the maximum speed at which both models are able to execute each of the circuit curves (V_n) without overturning. The approximate values of the speeds and parameters of the 3 and 5 DOF models are shown in the table 2.

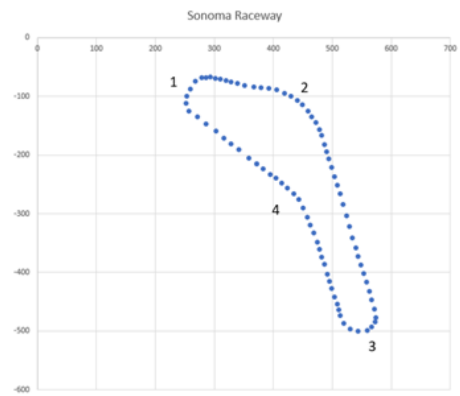

Fig 13. Curves Segmentation of the Sonoma Raceway.

Once the variation of the kinetic energy in each of the curves was calculated for both models, the sum of all values is determined. Thus, the total energy dissipated in one circuit is obtained in Table 3. With the results, it is noted that the 5 DOF model presents an energy saving of almost 40% referring to the braking at the entrance of each of the curves shown in Fig 13, when compared to the 3 DOF model. Thus, it is fair to affirm that the addition of a front suspension system in ultra-efficient automotive prototypes directly contributes to its energy efficiency in curves.

TABLE 2
PARAMETERS OF 3 AND 5 DOF MODELS.

Parameter	3 DOF Model	5 DOF Model
Reference velocity (V_r)	7.0 m/s	7.0 m/s
Maximum velocity in curve 1 (V_1)	4.5 m/s	5.0 m/s
Maximum velocity in curve 2 (V_2)	5.5 m/s	6.5 m/s
Maximum velocity in curve 3 (V_3)	4.5 m/s	4.5 m/s
Maximum velocity in curve 4 (V_4)	4.5 m/s	7.0 m/s
Maximum mass of vehicle with driver (M_t)	85.7 kg	85.7 kg
Suspension system mass of wheel 1 (m_1)	-	2.8 kg
Suspension system mass of wheel 2 (m_2)	-	2.8 kg

TABLE 3
DISSIPATED KINETIC ENERGY OF 3 AND 5 DOF MODELS.

Parameter	3 DOF Model	5 DOF Model
Kinetic energy of curve 1 (E_{k1})	1231.6 J	1096.0 J
Kinetic energy of curve 2 (E_{k2})	803.2 J	308.2 J
Kinetic energy of curve 3 (E_{k3})	1231.6 J	1313.0 J
Kinetic energy of curve 4 (E_{k4})	1231.6 J	0
Total kinetic energy	4498.0 J	2717.2 J

4 CONCLUSION

The present work sought to carry out the dynamic modeling of an ultra-efficient automotive prototype, taking as a reference the vehicles designed by UFSC's Energy Efficiency team. Based on the dynamic model of the vehicle, the study extended to the physical and mathematical analysis (theoretical) of the inclusion of a front suspension system in the prototype, with the objective of improving its performance in curves. Thus, the need for drastic braking is minimized, which implies a lower speed resumption at the exit of the curve and, consequently, makes the vehicle more efficient. For conducting the track simulations, the official Shell Eco-marathon circuit (adapted from Sonoma Raceway, CA) was mapped.

Among all the evaluations performed, the results regarding the vehicle's rollover were more satisfactory. Through the graphics, it was possible to notice a significant reduction in the force applied to the tire, when the prototype had a front suspension system. The analysis of rollover possibility during the circuit were shown higher for the 3 DOF model (without suspension) and lower for the 5 DOF model (with suspension). In terms of energy efficiency, the 5 DOF model has an energy saving of almost 40% referring to the braking at the entrance of each curve, when compared to the 3 DOF model, proving that the addition of a front suspension system in ultra-efficient prototypes directly contributes to its energy efficiency in curves. Therefore, it is safe to affirm that the study of the dynamic of ultra-efficient prototypes is very important for the understanding of all critical driving situations that can affect its performance. It is possible to make in-depth analysis and develop specific systems that will improve the performance of the vehicle dynamics.

5 ACKNOWLEDGMENTS

The authors thank UFSC Eficem group for provision of prototype data and competition information.

REFERENCES

[1] F. Arpino, G. Cortellessa, A. Frattolillo, F. Iannetta and M. Scungio, "Numerical and experimental investigation of the flow over a car prototype for the Shell Eco Marathon," *Journal of Applied Fluid Mechanics*, vol. 12, no. 1, pp. 207-218, 2019.

[2] J.C. Páscoa, F.P. Brójo, F.C. Santos and P.O. Fael, "An innovative experimental on-road testing method and its demonstration on a prototype vehicle," *Journal of Mechanical Science and Technology*, vol. 26, no. 6, pp. 1663-1670, 2012.

[3] M. Targosz, W. Skarka and P. Przystalka, "Model-Based Optimization of Velocity Strategy for Lightweight Electric Racing Cars," *Journal of Advanced Transportation*, pp. 1-20, 2018.

[4] M. Fabian, M. Puškár, R. Boslai, M. Kopas, S. Kender and R. Huňady, "Design of experimental vehicle specified for competition Shell Eco-marathon 2017 according to principles of car body digitisation based on views in 2D using the intuitive tool Imagine & Shape CATIA V5," *Advances in Engineering Software*, vol. 115, pp. 413–428, 2018.

[5] C.J.J. Paredis, C. Bishop and D.L. Bodner, "Systems Engineering (LSE): hands-on experiences in applying LSE to a student eco-car build project," *Procedia Computer Science*, vol. 16, pp. 492-501, 2013.

[6] V.D. Nguyen and P. Martin, "Product design-process selection-process planning integration based on modeling and simulation," *Int J Adv Manuf Technol*, vol. 77, pp. 187-201, 2015.

[7] Shell, "Shell Eco-marathon History," *Shell*, http://www.shell.com/energy-and-innovation/shell-ecomarathon.html, 2016.

[8] J.M.G. Rebelo and M.A.R. Silvestre, "Development of a Coreless Permanent Magnet Synchronous Motor for a Battery Electric Shell Eco Marathon Prototype Vehicle," *Open Eng.*, vol. 8, pp. 382–390, 2018.

[9] J.C. Olivier, G. Wasselynck, S. Chevalier, B. Auvity, C. Josset, D. Trichet, G. Squadrito and N. Bernard, "Multiphysics modeling and optimization of the driving strategy of a light duty fuel cell vehicle," *International Journal of Hydrogen Energy*, vol. 42, pp. 26943-26955, 2017.

[10] S. Jan, "Minimizing the fuel consumption of a vehicle from the shell eco-marathon: a numerical study," *ESAIM: Control, Optimisation and Calculus of Variations*, vol. 19, pp. 516-532, 2013.

[11] Z. Czyż, P. Karpiński and S. Koçak, "Numerical analysis of the influence of particular parts of the high efficient electric vehicle on the aerodynamic forces," *Advances in Science and Technology Research Journal*, vol. 13, no. 4, pp. 1-7, 2019.

[12] A. Messana, L. Sisca, A. Ferraris, A.G. Airale, H.C. Pinheiro, P. Sanfilippo, and M. Carello, "From design to manufacture of a carbon fiber monocoque for a three-wheeler vehicle prototype," *Materials*, vol. 12, no. 332, pp. 1-11, 2019.

[13] J. Sawulski and M. Ławrynczuk, "Optimization of control strategy for a low fuel consumption vehicle engine," *Information Sciences*, vol. 493, pp. 192–216, 2019.

[14] S.M.H.S. Omar, N.M. Arshad, I.M. Yassin, M.H.A.M. Fakharuzi and T.A. Ward, "Design and optimization of powertrain system for prototype fuel cell electric vehicle," *Journal of Mechanical Engineering and Sciences*, vol. 8, pp. 1401-1413, 2015.

[15] M. Omer, "Design and Analysis of Composite Chassis for Shell Eco Marathon Prototype Vehicle 2016 using Finite Element Analysis," *German University of Technology in Oman*, Oman, 2015.

[16] J.J. Santin et al "The World's Most Fuel-Efficient Vehicle: Design and Development of PAC-CAR II," *Zürich: vdf Hochschulverlag Ag an der ETH Zürich*, 2007.

[17] B. Fréchède, A.S. McIntosh, R. Grzebieta, M.R. Bambach, "Characteristics of single vehicle rollover fatalities in three Australian states (2000–2007)," *Accident Analysis and Prevention*, vol. 43, pp. 804-812, 2011.

[18] E.Ch. Tsirogiannis, G.E. Stavroulakis and S.S. Makridis, "Electric Car Chassis for Shell Eco Marathon Competition: Design, Modelling and Finite Element Analysis," *World Electric Vehicle Journal*, vol. 10, no.8, pp. 1-13, 2019.

[19] J. Kral, M. Palko, M. Palko and L. Pavlikova, "Design and development of ultra-light front and rear axle of experimental vehicle," *Open Eng.*, vol. 10, pp. 232–237, 2020.

[20] K. Jezierska-Krupa, M. Krysiak and W. Skarka, "Advanced driver safety support systems for the urban type vehicle," *Transport Problems*, vol. 10, no. 4, pp. 138-148, 2015.

[21] K. Jezierska-Krupa and W. Skarka, "Design method of ADAS for urban electric vehicle based on virtual prototyping," *Journal of Advanced Transportation*, pp. 1-18, 2018.

[22] M.R. Bambach, R.H. Grzebieta and A.S. McIntosh, "Thoracic injuries to contained and restrained occupants in single-vehicle pure rollover crashes," *Accident Analysis and Prevention*, vol. 50, pp. 115-121, 2013.

[23] B.D. Carlsen and O. Oma, "Development, Building and Competing with a New Car in Shell Eco-marathon," *Master of Science in Mechanical Engineering*, Norwegian University of Science and Technology, 81p, Jul, 2017.

[24] J. Reimpell, H. Stoll and J.W. Betzler, "The Automotive Chassis: Engineering Principles," *Butterworth-Heinemann*, 2. ed, 2001.

[25] T.D. Gillespie, "Fundamentals of Vehicle Dynamics," *Society of Automotive Engineers Inc*, 1992.

[26] M.P. Czechowicz and G. Mavros, "Analysis of Vehicle Rollover Dynamics Using a Highfidelity Model," *Vehicle System Dynamics*, vol. 52, no. 5, pp. 608-636, 2014.

[27] S-K Chen, N. Moshchuk, F. Nardi, and J. Ryu, "Vehicle rollover avoidance," *IEEE Control Systems Magazine*, pp. 70-85, 2010.

[28] G. Genta and L. Morello, "The Automotive Chassis: Volume 2 System Desing," Berlin: *Springer*, Mechanical Engineering Series, 2009.