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Article

Design and simulation of a suspension system for a four-wheeled HPV

Diseño y simulación de un sistema de suspensión para un HPV de cuatro ruedas

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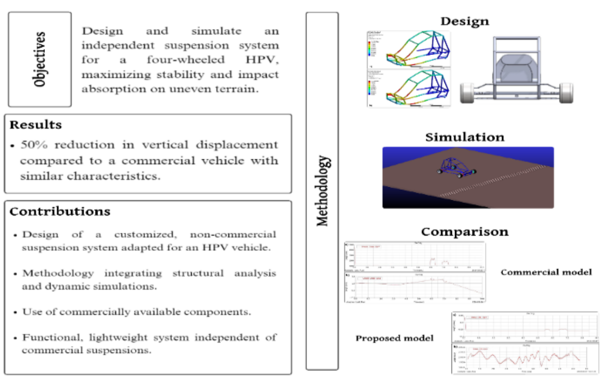
Abstract

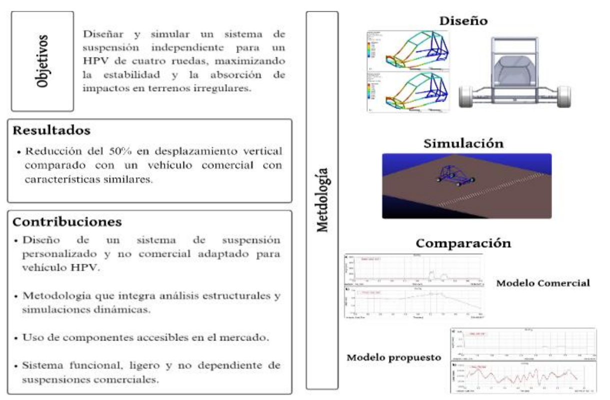
This work presents the design and simulation of a suspension system for a four-wheel, single-rider human-powered vehicle (HPV) to enhance stability and maneuverability on uneven terrain. The system, designed with lightweight components such as springs and shock absorbers available on the market, avoids the use of complete commercial suspensions. Static structural analyses using finite element methods were conducted to evaluate materials and geometries, along with dynamic simulations in MSC ADAMSDD. A comparison of the vertical and lateral displacement of the center of mass between the proposed system and a similar commercial model showed a 50% reduction in vertical displacement. This system improves impact absorption and HPV stability while meeting functional requirements and using accessible materials, making it an effective and cost-efficient solution for this type of vehicle.



Mechanical-Design, FEA, Dynamic-Simulation

Resumen

En este trabajo se presenta el diseño y simulación de un sistema de suspensión para un vehículo de propulsión humana (HPV) de cuatro ruedas y un tripulante, que mejora la estabilidad y maniobrabilidad ante irregularidades del terreno. El sistema, diseñado con componentes ligeros como resortes y amortiguadores disponibles comercialmente, evita el uso de suspensiones completas. Se realizaron análisis estructurales estáticos con elementos finitos para evaluar materiales y geometrías, además de simulaciones dinámicas en MSC ADAMSDD. Comparando el desplazamiento vertical y lateral del centro de masa del diseño propuesto frente a un modelo comercial similar, se obtuvo una reducción del 50% en el desplazamiento vertical. Este sistema mejora la absorción de impactos y la estabilidad del HPV, cumpliendo con los requisitos funcionales y utilizando materiales accesibles, lo que lo convierte en una solución eficaz y económica para vehículos de este tipo.



Diseño-mecánico, FEA, Simulación-dinámic

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Introduction

The suspension system is one of the most important when talking about vehicles, as it has a direct impact on passenger comfort. This system not only keeps the passenger comfortable, but also has a mechanical function, which isolates the body from the irregularities of the terrain, damping the disturbances that occur through the tyres. Explicitly, it is determined that the suspension of a vehicle is the set of organs and parts that are responsible for absorbing and damping the irregularities that occur when driving, which prevents the oscillations that originate in the wheels (due to the driving conditions) from being transmitted to the occupants of the vehicle; in such a way that the adherence of the wheels to the ground and the stability of the vehicle is favoured (Cebolla, 2017).

Suspension systems are classified according to the behaviour of their components during movement and disturbances. Dependent suspensions connect the wheels via a rigid axle, transmitting the movement from one wheel to the other. In contrast, independent suspensions (see Figure 1) allow each wheel to oscillate vertically without affecting the other, adapting better to pavement conditions (Vázquez, 2011).

Box 1

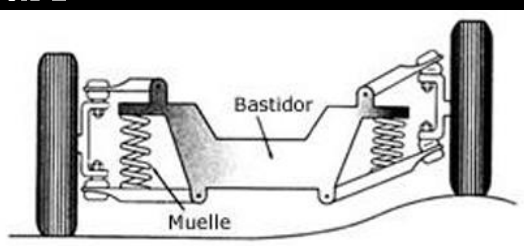

Figure 1
Independent suspension system

Source: Onion, 2017

Recent studies have focused on optimising both the structural stiffness and dynamic behaviour of vehicles, using advanced techniques such as Finite Element Analysis (FEA) and dynamic simulations. For example, Pulido (2014) performed a ¼ and ½ vibrational analysis of the Formula Student vehicle, determining the natural frequencies of the suspension to optimise shock absorption and improve the system's rebound and pitch response.

Additionally, their study on mass transfer during acceleration and braking demonstrated a significant improvement in vehicle stability, increasing the vehicle's handling under demanding conditions. In the field of lighter vehicles, such as go-karts, Gonza (2023) highlights that, although they lack a suspension system, the structural design of the chassis withstands torsional and bending stresses, providing the necessary rigidity to handle loads during acceleration and cornering, improving overall stability. Similarly, in the design of the Formula SAE electric single-seater, Auquilla & Torres (2016) performed a dynamic analysis with ADAMS/Car software, where they simulated constant radius curves and straight-line obstacles, validating the suspension design. Their results showed improvements in camber variation and spring movement, which contributed to better handling and stability, highlighting a low centre of gravity for optimal track performance.

Unlike previous studies, this work focuses on the design and simulation of an independent suspension applied to a four-wheel human-powered vehicle (HPV). While other studies have focused on optimising the suspension of vehicles with engines or on unsprung structures, this work uses an innovative approach in the implementation of lightweight and commercially available materials, such as AISI 4130, together with extensive finite element analysis (FEA) and dynamic simulations in MSC ADAMS®.

The main objective is to demonstrate a significant reduction of the vertical and lateral displacement of the centre of mass of the HPV, validating the improvement in stability and manoeuvrability compared to commercial models without suspension, making this study a contribution in the field of vehicles.

Design criteria

The design of the suspension system for the human-powered vehicle (HPV), incorporated in all four wheels, must meet several essential criteria. The system should be as light as possible, selecting commercially available springs and dampers, avoiding the use of full commercial suspensions. In addition, it is required to design a coupling system to the vehicle chassis that ensures optimal integration.

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It is essential to demonstrate a significant reduction in the vertical displacement of the vehicle's centre of mass in the event of road irregularities, compared to a commercial vehicle (see Figure 2) that does not have a suspension system.

Box 2

Figure 2
Go-Kart type commercial vehicle from Kart Leon products with similar characteristics to the proposed design

Methodology

Structural static analysis of the proposed chassis

To determine the material from which to propose the vehicle chassis, it is necessary to perform a finite element analysis. Srivastava et al. (2021) propose to subject the chassis to a frontal impact to assess its strength and ensure that both the material and the chassis structure will be able to withstand extreme conditions, such as severe external shocks or forces. Equation 1 is used to calculate the magnitude of the impact force, which considers that the force applied is four times the weight of the loaded vehicle, because in situations such as collisions or sudden accelerations, the forces acting on the chassis can be greater than its static weight.

$$F = m \cdot a = 4 \cdot 40 \cdot 9.81 = 1570\ N \qquad [1]$$

The boundary conditions applied are the previously calculated force, which is applied at the front of the chassis, and a fixed support at the rear axle.

The same model was analysed with different materials, considering factors such as strength, ductility, light weight, ease of welding, ease of machining, material cost and market availability.

The three materials to be considered are AISI 1018, AISI 1020 and AISI 4130, which are most commonly used in SAE competitions; the mechanical properties of each are shown in Table 1 in green. Relevant information such as total deformation, static safety factor and Von-Mises stresses were obtained from each experiment. The values obtained are shown in Table 1 in blue.

Box 3

	MATERIAL		
	AISI 1018	AISI 1020	AISI 4130
Density (g/cc)	7.87	7.87	7.87
Yield stress (MPa)	370	294.74	460
Ultimate Effort (N/mm^2)	440	394.72	560
Young's modulus (GPa)	205	210	210
Total Deformation (mm)	1.7751	1.8195	1.7328
Effort to Von-Mises Effort (MPa)	313.98	313.98	313.98
Safety factor	1.1784	0.93972	1.4651

Table 1
Mechanical properties of AISI 1018, 1020 and 4130 and simulation results for chassis design

Figure 3a and 3b show the total deformation in two tests, as an example, so that the change in deformations across the chassis as the load is applied can be seen. In both cases, the maximum deformation occurs at the front of the chassis, which is where the force is applied. With the data obtained in Table 1, it is determined that the appropriate material to use in the analysis model is AISI 4130, as it has the highest safety factor and the lowest total deformation.

Box 4

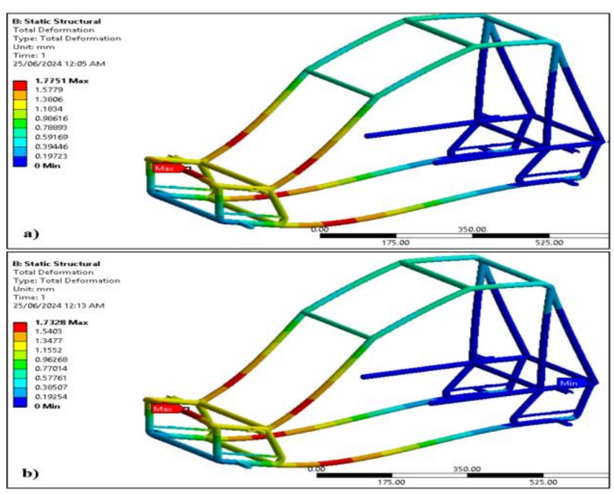

Figure 3
a) Total deflection of the proposed chassis with material AISI 1018; b) Total deflection of the proposed chassis with material AISI 4130.

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Description of the proposed suspension system

Figure 4 shows the proposed design of the suspension system.

Box 5

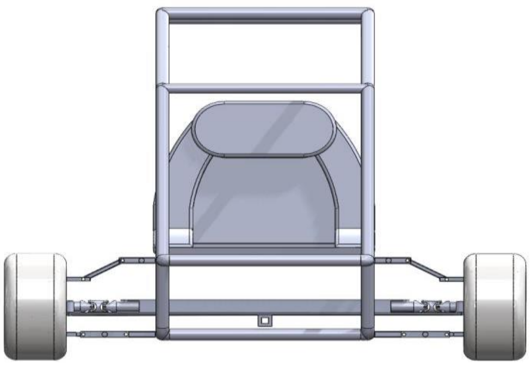

Figure 4
3D model of the proposed HPV vehicle chassis.

Figure 5a shows a more detailed picture of the suspension system, which is replicated on each wheel. The suspension system is independent and consists of two rotation joints (enclosed in red) which help to generate the longitudinal and transverse displacements; and two support mechanisms to guide the individual movement (blue), which serve as forks and join the hub carrier to the chassis, thus providing better support for the wheels.

Box 6

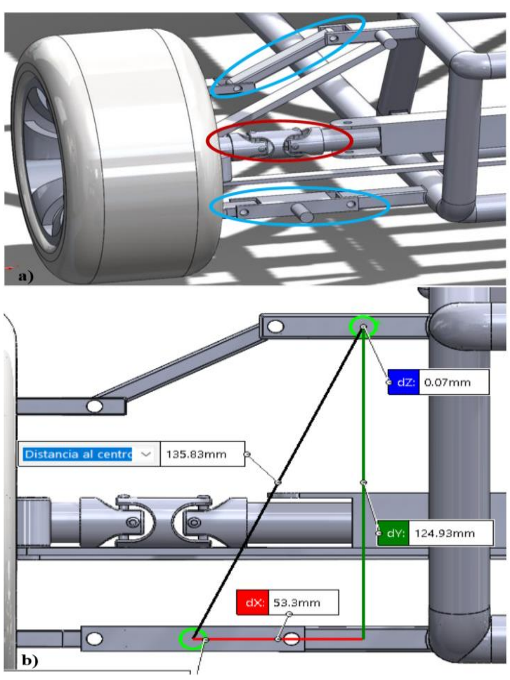

Figure 5
a) Detailed view of the suspension system;
b) Measured distance for shock absorber selection.

Shock absorber selection

To make the selection of the shock absorber, composed of the spring-shock absorber system, the distance between centres of the places destined to have the suspension, which measure 135 mm between centres, was considered, as shown in Figure 5b.

With the previous information considered, a bicycle shock absorber from the Taiwanese group, model DV-22AR marketed at DHgate, was selected (see Figure 6).

The main challenge for the designer is to find commercially available components that adequately fit the geometry of the design. In this case, the bicycle suspension measures 150 mm end-to-end, with a centre-to-centre distance of approximately 135 mm, making the shock compatible with the proposed design

Box 7

Figure 6
Selected shock absorber, model DV-22AR

Dynamic analysis in MSC ADAMS

To perform the motion analysis in ADAMS, it is important to consider the appropriate mechanical properties in each body. In this case, in addition to considering the mechanical properties of AISI 4130 steel shown in Table 1, the mechanical properties of natural rubber were also used. According to Connor (2021), the density of rubber is 110 kg/m3, Young's modulus is 0.05 GPa and Poisson's coefficient is 0.2.

Figure 7 shows the road or track where the test for the suspension system will be carried out. This road consists of a flat surface and a series of irregular bumps, which were created to observe the behaviour of the vehicle's centre of mass under a perturbation such as the one generated when passing over bumps.

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Box 8

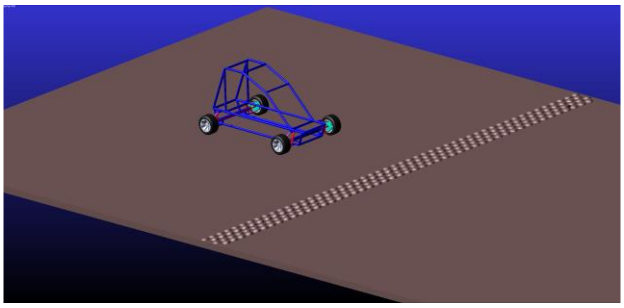

Figure 7
Road to travel.

In addition, the static and dynamic coefficient of friction of the springs is considered to be μ=0.5 (Arosemena, 2024).

Description of torque and speed in the model

For the analysis of the suspension of the vehicle, a torque with a magnitude of $1\ N/m$, in a time of $t = 0.5\ s$, Afterwards, the torque is released, and at about $t = 3$ se now apply a negative torque with a value of $-1\ N/m$, which is maintained for a short period of time, until it is permanently removed. The first torque that is added to the system is to accommodate the vehicle on the track; the second torque is to give it a movement in the direction of passing the stops shown in Figure 7).

Box 9

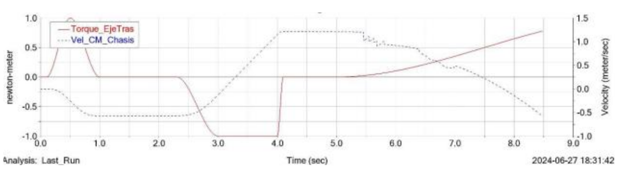

Figure 8
Torque and Speed Graph of the proposed model

On the other hand, the speed at which the vehicle moves is of utmost importance. That is why, in Figure 8, the chassis speed graph is shown (blue dotted line). In this graph it can be seen that in the first two seconds, the vehicle acquires a negative speed, this means that the vehicle is moving backwards to accommodate itself and later, it passes from the negative to the positive frame, reaching a maximum of 1.3 m/s and its speed is maintained until it encounters obstacles in its path; this is why, from the sixth second, a distortion and decrease in the magnitude of the speed can be seen in the image, this is because the vehicle passes over the stops, decreasing its speed.

Results

To verify the proper functioning of the suspension system, the proposed model was compared with a commercial model with similar characteristics without any suspension system. Vertical and lateral displacement plots of the centre of mass of the commercial model were obtained, corresponding to the y-axis and z-axis, respectively. These plots are shown in Figure 9a and 9b, respectively.

Box 10

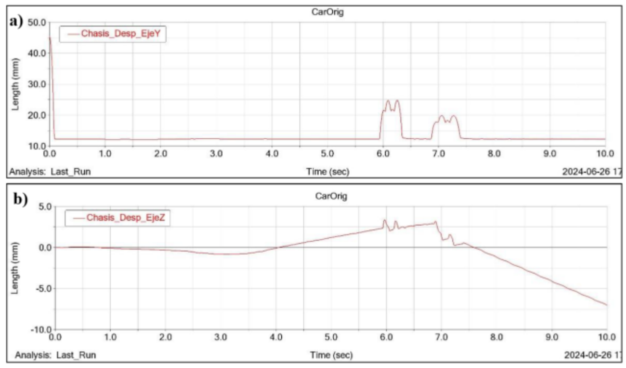

Figure 9
Vehicle displacement graph of vehicle with similar characteristics: a) on the axis *y*, b) on the axis *z*

Figure 9a shows the vertical displacement of the centre of mass, where the centre of mass remains in the same position until the vehicle suffers a disturbance (t= 6 s). These lobes refer to when the front tyres pass over the stops that were placed on the track, after a few seconds, the centre of mass suffers another alteration, due to when the rear tyres pass over the same stop. If the same figure is observed, it can be seen that the largest displacement is suffered when the front tyres manage to pass the stops, generating a displacement of the centre of mass of approximately 25 mm.

On the other hand, Figure 9b shows the lateral displacement of the centre of mass, which is equivalent to observing how the vehicle moves when facing forward. As mentioned before, at a time (t= 6 s), is when the vehicle starts to pass the bumpers; remember that this commercial vehicle does not have a shock absorber, so when faced with a perturbation such as the bumpers, every time the front or rear tyres come into contact with the bumpers, the movement of the tyres is transmitted directly to the chassis.

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From the graph, it is determined that the largest displacement of the centre of mass at *axis z*, is +3.25 mm, approximately; and corresponds to the instant of time when the first tyre comes into contact with the road bumps.

To observe the behaviour of the vehicle with the proposed suspension system, the results of the displacement of the vehicle's centre of mass were also obtained, both for the y-axis and for the z-axis. This information can be seen in Figure 10a and 10b, respectively..

Box 11

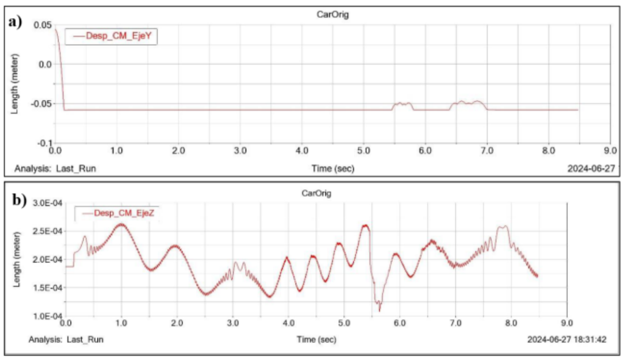

Figure 10
Displacement plot of the proposed vehicle: a) on the y-axis, b) on the z-axis

In the case of the y-axis displacement, the centre of mass is not displaced until a time t= 5.5 s, which is when the front tyres start to pass the stop, and when the rear tyres meet the stones, displacement occurs again. However, the largest displacement occurs when the rear tyres pass the series of stops, thus presenting a displacement of approximately 12 mm.

The z-axis graph has a peculiar but very interesting behaviour, as it shows the effect of a shock absorber in generating a harmonic movement. If Figure 10b is observed carefully, the magnitude of the displacement graph is relatively close to zero; in addition, the damping effect (damping coefficient) has a direct effect on the shape of this signal, as this coefficient indicates the amount of energy that can be absorbed by the system in motion.

Table 4, which contains the most relevant information from each analysis, shows the maximum displacements obtained in each experiment.

Box 12

	Maximum displacement	
	Vertical (mm)	Lateral (mm)
Vehicle Go Kart-León	25	3.25
Proposed vehicle	12	2.50E-04

Table 2
Maximum displacements in both vehicles

The most noticeable difference in the two models is the lack of a shock absorber on the commercial vehicle; therefore, when the vehicle traversed the same track as the proposed vehicle, the centre of mass shifted noticeably vertically. Numerically speaking, the displacement was almost halved with the addition of the suspension.

Conclusions

The implementation of the chassis is capable of supporting the load applied to it and the highest safety factor has a value of 1.17, under the mentioned conditions and with AISI 4130 material; which means that under a frontal impact of 4 times the magnitude of the vehicle weight, it still presents low stress magnitudes and deformations around its structure; that is why this material was chosen for the simulation of the vehicle in MSC ADAMS®.

Through the motion analysis in MSC ADAMS® it was possible to verify numerically the advantage of the created model over a commercial model, obtaining that thanks to the suspension system that the model has, the displacement of the centre of mass in the , can be reduced from 25 mm to 12 mm, which is equivalent to 52%, and in the case of the lateral displacement (), the displacement is reduced almost entirely, because the shock absorber performs the function of absorbing the energy due to the movement.

There are several opportunities to improve the design of the suspension and chassis system. One of the main areas of optimisation is the implementation of more detailed topology analysis to further reduce weight without compromising structural rigidity. In addition, the incorporation of advanced materials, such as fibre composites, could improve the strength-to-weight ratio, offering greater efficiency.

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Experimental tests to complement the simulations would also be beneficial to validate the performance of the system in real conditions and adjust the design based on the data obtained. Finally, optimisation of the damper design and its interaction with the suspension elements could lead to greater vibration absorption, further improving vehicle comfort and stability.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that might have appeared to influence the article reported in this paper.

Author's contribution

The contribution of each researcher in each of the points developed in this research was defined on the basis of the following:

Contreras Chávez Axel Aldahir: He contributed in the conceptualisation, methodology, software, research and writing.

Pérez Cruz Melissa Yamileth: Contributed to the conceptualisation, methodology, software, research and writing.

Villagómez Moreno José: Contributed to the drafting, revision and administration of the project.

Manríquez Padilla Carlos Gustavo: Contributed to the drafting, revision and administration of the project.

Availability of data and materials

For the availability of information and material relating to this work please contact the author contact.

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Abbreviations

FEA	Finite Element Analysis (Análisis por Elementos Finitos)
HPV	Human-Powered Vehicle (Vehículo de propulsión humana)

References

Background

Cebolla Bono, B. (2017). *Modelling and characterisation of suspension systems in motor vehicles* (Doctoral dissertation, Universitat Politècnica de València).

Vázquez Trevilla, N. I.(2011). *Design of vehicle suspension system formula SAE* (Doctoral dissertation, Universidad Autónoma de México).

Basic concepts

Connor, N. (2021). *Rubber | Density, strength, melting point, thermal conductivity*. Material Properties. [Online]. Revised May 2024
Srivastava, J. P., Chaithanya, B. K., Teja, K. S., Venugopal, B., Vineeth, S., Rajkumar, M., &

Khan, H. (2021). *Numerical study on strength optimization of Go-Kart roll-cage using different materials and pipe thickness*. Materials Today: Proceedings, 39, 488-492.

Arosemena, A. (n.d). *Mechanical springs*. [Online]. Revised May 2024

Supports

Auquilla Ocampo, J. L., & Torres Romero, C. R. (2016). *Design of the suspension system of an electric single-seater vehicle Formula SAE* (Bachelor's thesis).

Pulido Laparra, C. (2014). *Design of the suspension system for a Formula Student vehicle.* Carlos III University of Madrid.

Differences

Gonza Valle, R. E. (2023). *Design and construction of a go-kart type vehicle with tubular structure*. Instituto Superior Tecnológico Vida Nueva.

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