# BAMBOO, the wonder material to reinvent mobility.

"Automotive, Sports and Recreation Industry"

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## Abstract.

The following article is a general reflection on the evolution of the use of bamboo in solutions for human mobility, from the early day bicycles to the actual automotive industry, demonstrating that bamboo can be a wonder material to reinvent the way vehicles are conceived. This paper also presents the creation of the world's first bamboo soapbox racer developed in 2017 as the initial project on a more ambitious plan to develop light, efficient, safe, renewable materials made vehicles.

Bamboo has been used as a construction material over centuries to build from simple shelters to towers and bridges and the scaffolding used to build them. Due to the lightweight to strength ratio, Bamboo is a versatile material that has also been used in many other products as fishing rods, musical instruments, kitchen utensils and bicycles.

The knowledge and experience acquired over the years together with the manufacturing techniques available today make bamboo and bamboo engineered products to set the key to lightweight and efficient-clean vehicles construction.

The transport sector is the largest contributor to NOX emissions inside the cities accounting for 46 % of total EU-28 emissions in 2014 according to the "*Air quality in Europe - 2016 report*" published on the 2016 by the European Environment Agency. While the population is increasing in urban areas, the quality of the air that citizens breathe is decreasing rapidly. According to the European Commission, every year more than 400.000 people in the EU die prematurely due to the consequences of air pollution: this is more than 10 times the toll of road traffic accidents. Therefore it is imperative to act urgently to comply with the goals and prevent greater damage to the environment and the people.

By creating lighter, more efficient vehicles using renewable materials, humanity will be closer to achieve a sustainable future.

# 1. Introduction.

The actual global trend in automotive industry is to lower the weight of components to achieve better fuel efficiency. The global warming, the climate change and the unsustainable models of actual production using non-renewable resources have set the alarms that are forcing the industry to search for alternative construction methods and materials to preserve the environment.

Scientists have been researching the potential use of natural materials like wood, grass and plants for many decades. Since natural resources could be unlimited, if we take good care of them, the use of renewable materials demonstrate that these are the great alternative to non-renewable materials such as steel, aluminium, plastics or synthetic fibers.

According to the *'World Atlas of Bamboo and Rattans'* (Vorontsova et al. 2016) [1] there is 1642 species of bamboo classified. Mechanical properties of some of the species as the high strength-to-weight ratio and the excellent vibration control, make this an ideal building material for low-impact, earthquake-resistant housing projects, as well as for many other applications such as huge skyscraper scaffolding, windmills, buildings, bridges, musical instruments or even bicycles.

It could seem that bamboo bicycles are something fairly new, but there are records of bicycles constructed using bamboo frames as far as in 1894 when a bicycle developed by the Bamboo Cycle Company (Figure 1) was presented at the London Stanley Show (English patent 8274 April 1894) [2].

Bamboo Cycle Co. Ltd. Bicycle. Catalogue p.2 images from 1897. (Figure 1)

Unfortunately bamboo made bicycles had a minor impact on global sales during the XX century. The simpler and more controllable assembling methods used with steel or aluminium frames along the higher costs of production and acquisition of bamboo bicycles, made that these could not win the battle at that time. Nowadays overcrowded cities, pollution and health problems play a significant role to change the way we develop means of transport. With knowledge, improved testing and assembling techniques and sustainable consciousness, we have the opportunity to place bamboo again as the material to be used on mobility solutions.

# 2. The use of bamboo in actual bicycles construction.

In the beginning of this century bamboo bicycles appeared again and during the second decade, they have achieved a major boost. Some bamboo species are considered to be the optimal variants for bicycle frame construction, since they demonstrate higher tensile strength than some aluminium alloys which are already in use in top performance bicycle frames construction.

Based on the experience gained over the years the process of selection, treatment and use of bamboo culms has been refined and improved to achieve really light and robust bicycle frames.

There are many bamboo bicycles manufacturers all over the world, from high-tech quality made and controlled bicycles to simple functional means of transport. The idea of this section is not review the market but to analyse the state of the art of the bamboo use in bicycles construction.

The customers of bamboo bikes in the 'developed' countries are normally eco-conscious people that aim to contribute to a more sustainable future by using products developed in renewable materials, as well as cyclists that search for this type of frame construction due to the great strength to weight ratio and to the vibrations absorption that bamboo offers. On the other side the accessibility of this natural material in many countries allows that underdeveloped areas can construct their bamboo bicycles at really low costs.

## 2.1 Bamboo culms on bicycle frames construction.

Brazilian Flavio Deslandes started in 1995 developing his first bamboo bicycle and this was presented at the 5th International World Bamboo Congress in 1998 (Figure 2) [3]. Its frame was based on cable tensioning system Tensegrity to create a light structure and with the possibility of being removable for easier transport or replacement of components. Flavio graduated in 1999 with the bamboo bicycle prototype nr.2 being the final project (Figure 3). The first patent MU7901320-1 was applied in 1999 and granted in 2005 [4].

Flavio Deslandes #1 in 1998 (Figure 2)

Flavio Deslandes #*2* in 1999 (Figure 3)

The American Graig Calfee developed his first bamboo bike as a publicity stunt in 1995. That first design spawned 12 others for family and friends and the smooth ride that those first prototypes had made Calfee start the production of bamboo bicycles in 2005 [5] Since then Calfee Designs has been manufacturing all types of bamboo bicycles, initially using carbon fiber connection lugs shifting later to hemp-lugged made frames due to many of the carbon fiber joints failing over time.

The Argentinean Nicolás Masuelli started constructing bamboo bicycles on 2006 and since then has developed some of the most interesting bicycles, tandems and trolleys. Nicolás has also developed bamboo folding bicycles [6].

Nicolás Masuelli Tandem (Figure 4)

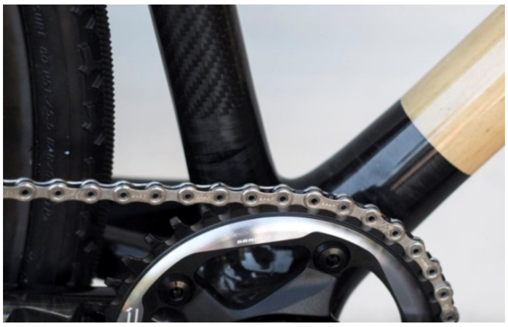
Nicolás Masuelli Folding bicycle (Figure 5)

The process used on the frame construction using bamboo culms is always similar starting with the selection and treatments of bamboo culms. The material or the type of connecting elements used to assemble the frame can be diverse. From synthetic materials as carbon fibers (Figure 9) or natural fibers as flax or hemp (Figure 7), connection lugs are created by combining the fibers with resins to create a perfect matrix that join the culms together in a solid manner. Steel (Figure 6) or aluminium (Figure 8) connecting lugs are also techniques that have been used to assemble frame components.

Bamboo Cycle Co. 1897 (Figure 6)

'Small SB0422' Calfee Design© (Figure 7)

Ross Lovegrove. Designboom© 2009 (Figure 8)



Boo Bicycles Cyclocross Magazine© (Figure 9)

Assembly rigs are a must to ensure proper geometric tolerances while skilled professionals are required to achieve high quality final products. Frame kits already prepared and assembly rigs can be acquired today through several manufacturers but a good technique can only be achieved by reading, learning, practicing and experimenting.

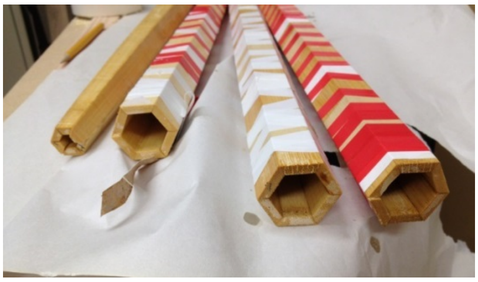
In 2011 Oxford Brookes University engineering students in collaboration with the Joining Technology Research Centre designed and developed a bicycle frame using bamboo and flax fibers to maximise bamboo's unique rigidity and vibration absorbing qualities. The Bamboo Bike (Figure 10) was certified to European safety standards demonstrating that bamboo is a suitable material for bicycle frames construction [7]. Another proof that bamboo bicycles are back to stay this time and that they can perform better than no-renewable contenders, is that on March 29th 2014, French cyclist Thibaud Lhenry (Figure 11) won with a bamboo bicycle the seventh Red Hook Criterium of New York, competing against more than 280 professional road racers [8].


Oxford Brookes bicycle. BBC© (Figure 10)

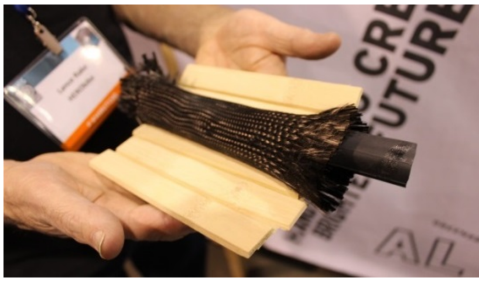
Thibaud Lhenry. RAW Cycling Mag© (Figure 11)

## 2.2 Bamboo engineered components on bicycle frames construction.

So far we have reviewed the examples that use bamboo culms as part of the frame but there are also other bamboo engineered solutions used on bicycle frames construction. The increasing offer of bamboo engineered products opens a greater range of possibilities for bamboo products construction, from flat multiplies components to flat or tubular woven structures. Inspired by bamboo fly rods, Professor Lance Rake developed the '*Semester Bike*' on 2011 using bamboo strips glued together forming hexagonal tubular shapes (Figure 12). Later on 2012 he upgraded the process using a bladder to expand and glue a braided carbon fiber sleeve (Figure 13) to the inner wall of the hexagonal tubes with epoxy resin. The continuous bamboo fibers running parallel to the tubes together with the carbon fibers diagonally laid provide the system a great torsional rigidity. The vibration dampening advantage compared to full carbon frames represents an affordable and eco-conscious solution [9].



Hexagonal tubes. Photos by L. Rake (Figure 12)



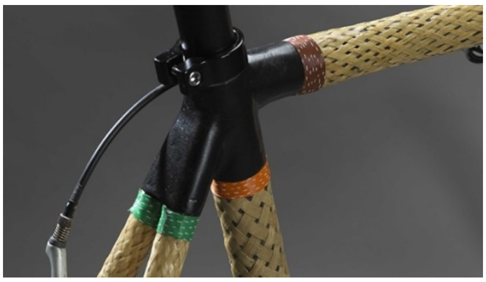
Detail image. Gizmag Pty Ltd. © (Figure 13)

The '*Flat pack*' concept developed by Professor Rake in 2013 used flat woven bamboo veneers and balsa wood as part of the exterior shell. (Figures 14 and 15) The interior core is made using 3D printed components and has carbon fiber and metal inserts on the rear drop-outs. This prototype evolved into product called '*Bamboost*'' which is produced by *HERO bike* in Alabama [10].

'Flat Pack'. Gizmag Pty Ltd. © (Figure 14)

'Flat Pack'. Gizmag Pty Ltd. © (Figure 15)

The '*Woven Tube*' bike (Figure 16) was another innovative bamboo / carbon fiber composite construction proposal by *Professor Lance Rake*, presented in the *North American Handmade Bicycle Show* in 2014. The concept explored the variability in tube dimensions that this construction system would allow (Figure 17). With an overall weight of 8,6 kilograms this bicycle offered a great shock absorption capacity and a stiffness similar to other steel and carbon made bicycles while still saving a lot of weight compared to using solid bamboo culms [11].



'Woven tube''. Core77 © (Figure 16)

Woven tubes. Core77 © (Figure 17)

Laminated bamboo components have also been found on bicycle frames as the '*Victoria'* (Figure 18) and '*Estrella'* (Figure 19), Bolt series models by Bambike, from the Phillipines [12].

'Victoria'. Bamb Eco Tech. Inc. © (Figure 18)

'Estrella'. Bamb Eco Tech. Inc. © (Figure 19)

The fact that these are engineered components means that they are always consistent in size, shape, and performance. These design approaches lead to more manufacturing friendly processes than using traditional bamboo culms, which need to be individually custom fitted and joined due to variations in tube diameter and wall thickness.

# 3. Bamboo used in other mobility solution projects.

Once that bamboo has been demonstrated as a great material for the construction of bicycles, from simple but solving mean of transport to high performance bicycle frames, it is the time to open bamboo onto all the other mobility solutions to address people's needs.

## 3.1 Bamboo culms on vehicle frame construction.

Several examples of bamboo culms being used for vehicle frame constructions have been found in different competition, as the eco-Shell marathon challenge vehicle from ESIETA [13], French University in 2008 (Figure 20) or the ASME human powered competition vehicle on 2015 developed by a team of students from the University of Alabama (Figure 21) [14]. These examples, which finished in second position in their competitions, show different working solutions that can be developed using this wonder material, from light weight vehicles to recumbent trikes.


Club Eco Marathon Shell Ensieta (Figure 20)


Alabama HPVC via Twitter (Figure 21)

Another vehicle construction approach using bamboo is found on '*Designing for Velomobile Diversity: Alternative opportunities for sustainable personal mobility*' paper, published at the *7th International Velomobile Seminar* on 2012, by Alexander Vittouris and Mark Richardson [15].

Focused on the conservation of the energy in the fabrication by using pre-harvest deformed bamboo sections, Vittouris addressed that current production methodologies for building bamboo vehicles are centred on using straight culm sections, and that alternatively both structural and vehicle outline shapes could be shaped as the bamboo grows using arborsculpture techniques. The '*Ajiro*' reverse trike concept (Figure 22) was the breed for the final prototype development (Figure 23)

‘Ajiro’ Concept. Vittouris (Figure 22)

‘Ajiro’. Picture by Melanie Faith-Dove (Figure 23)

Vittouris completed a PhD. with the Thesis ‘*Shaping bamboo prior to harvest*‘ (Vittouris 2017) [16] which is an interesting report based on vast experimentation and full of valuable information that shows alternative methods for the conception of bamboo structures and vehicle components.

## 3.2 Bamboo engineered components on vehicles construction.

Natural fibers have been used in the automotive industry mainly to fabricate interior trim, floor mats, or insulations components, but bamboo has just started to be used in the global scene. Ford has just recently questioned on a press release in April 2017 [17], <<***What's Super Strong, Fast Growing, and Potentially Part of Your Next Car??***>> Yes, ***Bamboo***. Janet Yin, a materials engineering supervisor at Ford’s Research & Engineering Centre in Nanjing, China, commented that the team had found that bamboo performs comprehensively better than other tested synthetic and natural fibers in a range of tests from tensile strength to impact strength.

Even if we can be optimistic with these kind of statements done by car manufacturers the reality is that bamboo is being only used for trims. Some examples are found on interior trims of the Lexus LS 600h (Figure 24) and on some components on the FIAT 500L Trekking ‘*Street Surf*’ showcar from 2014, where side view mirrors (Figure 25), hub caps, side protections, sill plates for doors, the luggage compartment platform, the gear knob and the parking brake lever used bamboo.


Lexus© LS 600h center console (Figure 24)

Fiat© 500L Trekking side view mirror (Figure 25)

Some other examples have been found on other concept vehicles, as footsteps (Figure 26) on the ‘*Rinspeed Bamboo*’ concept from 2011, and on the flooring and cockpit trims found on the ‘*Me.We*’ concept designed in 2013 by Toyota ED2 design studio (Figure 27)


Rinspeed© Bamboo Footstep (Figure 26)

Toyota© ‘Me.We’ interior (Figure 27)

In 2011, German product designer Albrecht Birkner and Philippines designer Kenneth Cobonpue presented at Milan Design Week 2011 the '*Phoenix*' concept vehicle. This lightweight concept was made completely out of bamboo, rattan (Figures 28 and 29) steel and nylon was assembled in 10 days by a team of skilled weavers and craftsmen. The creation aimed to challenge conventions by sourcing renewable materials from the earth and using a frame that is built by hand using very minimal tools and energy, paying homage to the skills of craftsmen [18].

'Phoenix' by A. Birkner and K. Cobonpue (Figures 28 & 29)

The first vehicle to employ a bamboo engineered chassis was developed by one of the world's key experts in bamboo the German *Jörg Stamm.* His experience in designing and constructing bridges, houses and other constructions led him to build an electric buggy in 2010 using bamboo as the main material on the chassis. Using single laminated and curved Guadua bamboo plies, the '*Bamboo Buggy*' (Figure 33) was able to carry around two people with no compromise. A really interesting analysis, '¿A qué escala es rentable la industrialización del Bambú?' (Stamm 2016) [19] presented at the Mexican Bamboo Congress held on March 2016, showed an image of the prototype (Figure 30).

Jörg Stamm 'Bamboo buggy' (Figure 30)

# 4. 'GOYTI' Bamboo soapbox racer.

Artistry and craftsmanship together with knowledge and engineering hold the key to develop new sustainable means of transport using bamboo as the primary material.

On the spring of 2017, Karl Niklass, 'Charlie' and Iván Platas started working on the idea of constructing a soapbox racer made out of bamboo to compete on a local race. The initial idea was to learn about bamboo but always foreseeing many other mobility solution designs.

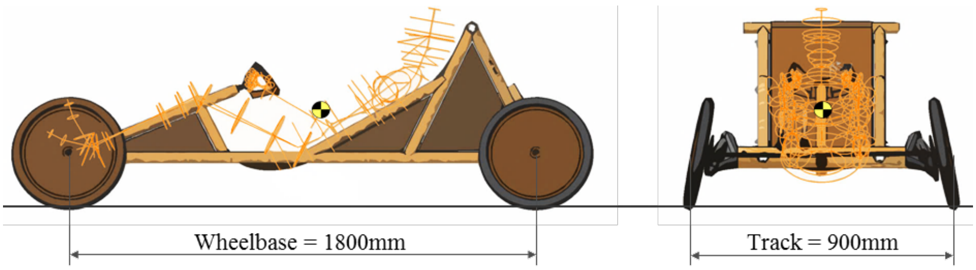
The great mechanical properties of bamboo and a clever design of the structure combining different diameter sections, allowed the creation of a chassis that performed on a superb way. This prototype propelled by gravity, served as an example on how natural materials can be optimal construction materials and better in many aspects, than those solutions made out of non-renewable materials.

A motorsport background, where optimal solutions and performance are pursued as the golden grail, this prototype kept on searching for the optimal efficiency, keeping the design as simple as possible. The ultimate goal was winning the competitions but applying a holistic approach where all the aspects are taken into account. Renewable materials and traditional techniques combined with new technologies were key aspects on the development of this prototype.

*Guadua* bamboo was used for the whole chassis construction. This project was completed in three months applying fundamental engineering and vehicle dynamics principles, careful time planning and project management techniques, similar to what it would be done in a real professional engineering project. The whole process involved the CAD design, the search for optimal materials, solutions and partners, auxiliary components and suppliers, the detailed cost control and analysis, reception and verification of goods, the assembly, set-up, tests and race.

The chassis was constructed by combining greater diameter culms (Ø 80mm) and solid joints on the front and rear members to achieve greater axle stiffness, and thinner culms (Ø 40mm) on the center part of the vehicle and flexible joints to achieve a greater torsional flexibility along the chassis. This approach was a key to achieving an optimal roll-warp chassis deformation to maximize the contact, grip and overall performance of the tires under cornering.

The design started with a rectangular chassis design of 1800 mm wheelbase and 900 mm track (Figure 31), to have a rectangular platform where to place the driver as centred as possible. Since an initial goal was to set the center of gravity as low as possible and a weight distribution among axles as equal as possible, the same tires were used all around and the driver was placed as low and central between the axles as possible.




Initial drawing of concept design (Figure 31)

The Guadua culms were supplied by BAMBUSA (Figure 32). The connections of the main longitudinal components of the chassis to the axles were created by drilling holes on these and assembling the culms across. These joints were secured by inserting wooden dowels top and bottom across both members (Figure 33). The transversal members were cut to length and adapted with bird's mouth cut outs to match the shape of the longitudinal main members (Figure 34). All these components of the chassis were joined together using dowels, ribbons and epoxy glue (Figure 35).

Guadua culms on reception (Figure 32)

Axle to longitudinal member connection (Figure 33)

Base chassis construction (Figure 34) Main chassis construction (Figure 35)

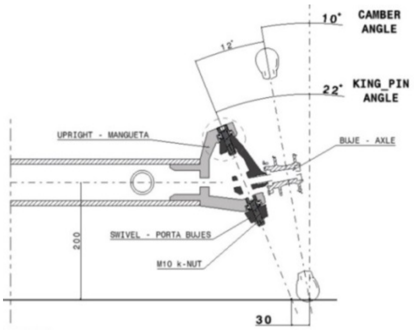
A single supported steering column was planned to keep the design as simple as possible. A kart steel rod column was acquired to connect steering wheel and steering rods (Figure 36). The assembly rotated around press fit bearings glued inside pre shaped pockets (Figure 37).

Steering rods connection (Figure 36) Steering column bearing housing (Figure37)

A recycled jute potato sack was used to construct the racing seat. Cutting and preparing it to shape, brass eyelets were fitted to fix it around the perimeter of the chassis using cords (Figure 38). Member joints were covered with jute cloth and sisal to give it a better finished appearance (Figure 39).

Bamboo Chassis on the scales (Figure 38) Connections and cosmetics (Figure 39)

Steering components were designed assuming extreme load cases and applying the fundamentals of steering and suspension design (Figure 40). These components were manufactured on PA12 nylon using a HP Multi Jet Fusion 3D printing machine thanks to the support of OPTIMUS3D. A template was developed to machine exact holes on the axles where the uprights were fixed by inserting wooden pegs (Figure 41). The final set up verifications proved really accurate geometric results.




Front axle section for assembly (Figure 40) Uprights assembly rig (Figure 41)

The brake pedal system was composed of two bicycle brake levers fixed to Ø 20mm wooden dowels inserted and glue onto the axle (Figure 42). Brake discs and hydraulic callipers were added on the front swivels to complete the braking system (Figure 43).


Brake pedal detail (Figure 42)


Chassis, steering and brakes (Figure 43)

The pusher device to add inertia to the racer at the start of the race was also developed using Guadua bamboo culms and similar joining methods as the racer. A coned shape area on the racer acted as the locating point for the pusher device, for a second team member to give it a good push applying its body weight on a leather belt secured to the pusher top end (Figure 44). The forefront cone was shaped using a bottle top end filled with esparto and glue (Figure 45).


Pusher handlebar and chest support (Figure 44)


Pusher bottom cone (Figure 45)

The final weight of the racer was 26 kg, with 17 of these corresponding to the bamboo chassis. A close 50 / 50 weight distribution was achieved with 51.4 kg (F) / 48.6 kg (R) measurements. The torsional stiffness of the chassis was tested along the assembling process by placing 80 mm blocks under the quarters of the chassis and loading the opposite corners. Checking that no major failures or cracks appeared validated this prototype. This torsional flexibility was proved during the races, as the vehicle maintained the wheels stuck to the ground all the time.


Set up before set down (Figure 46)


Set down ready for shake down (Figure 47)

On set up bases (Figure 48)

On August the 6th 2017, this construction became the world's first gravity racer to use bamboo as the main material on the chassis construction. The competition took place during the local festivity of Vitoria-Gasteiz, and was based on a three timed stints over a 250 meters track, a 10% mean gradient and three really fast corners. The bamboo racer was able to score one of the best five times among all racers and ended up awarded as the most original design among more than 20 contenders.

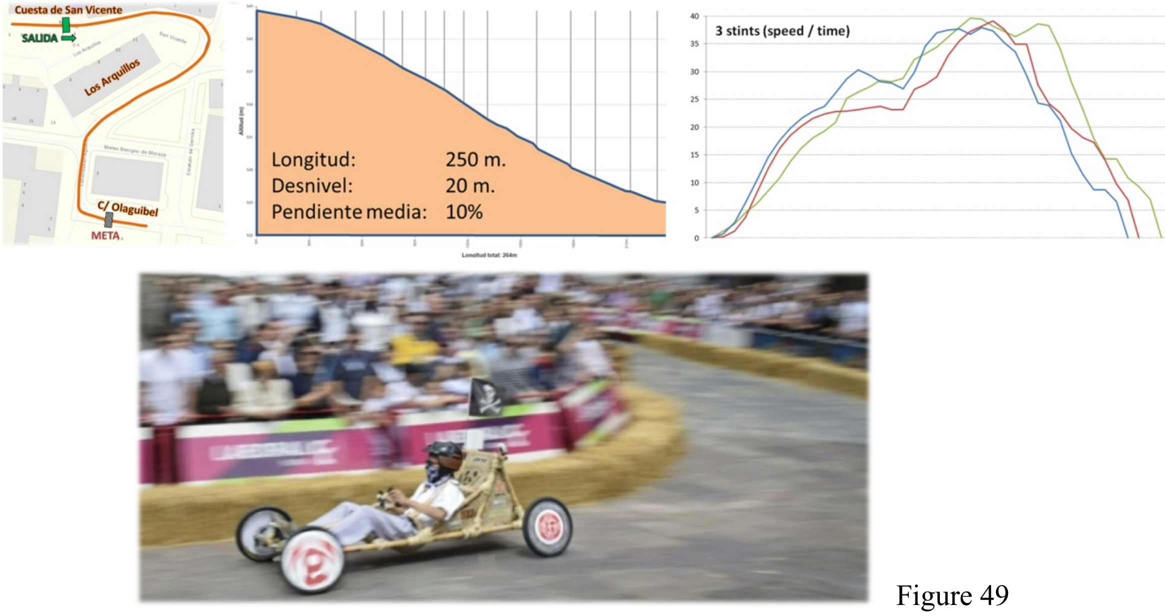



Figure 49

The second event where the bamboo racer competed took place one month later on Arroiabe, Álava, on the 9th of September. The track had 245 meters with a big initial gradient and different type of corners on the middle section. The speed GPS sensor recorded top speeds close to the 50 km/h, with cornering speed around the tightest corner of 30 km/h (Figure 50).


Figure 50

On this second race the bamboo soap box prototype scored the fastest time on the track on the final stint, which showed that the racer has a lot of potential. Becoming second on the overall ranking was really positive and a great final award for the first racing season.

## 5. Conclusions.

Bamboo is a wonder excellent material. The maturity of the construction techniques and the quality of the resultant bamboo made products satisfy the demand of the most exigent users, so we can state that bamboo and bamboo engineered products are optimal candidates to replace non-renewable materials on bicycle frames construction and on many other mobility solution derivatives.

While investment in research has gone into materials as synthetic fibers or lightweight alloys, bamboo is the renewable material that can have the key to change the paradigm of how mean of transports are constructed. Now, it is the time for hard working people to construct and present solutions that demonstrate that bamboo satisfies mobility needs in a sustainable way.

The first concern or reaction that users could have is that bamboo in not as a safe material to construct vehicles with. Developing prototypes as proof of concept of functional, safe and efficient transport solutions to solve people's needs, should be the goal to increase the use of this excellent material in the automotive industry.

Construction using BEP lead to more manufacturing friendly processes than using traditional bamboo culms, which need to be individually fitted and joined due to variations in tube diameter and wall thickness, but culms should also be used for tubular structures constructions when possible due to the fewer energy employed in their life cycle compared to bamboo engineered products.

Until the global mentality does not shift towards a paradigm where a sustainable future is the most important goal, these taskswill take much more effort. Understanding that the cost of keeping on with the actual manufacturing methods and materials is higher, due to the pollution and health problems derived from it, will make people's minds shift toward 'green' mobility solutions.

Replacing non-renewable materials with bamboo products in as many applications as possible must be an objective for future research projects. From chassis and suspension components, to interior and exterior trims, the commitment must be demonstrating that bamboo can be a wonder material to reshape mobility.

## 6. Figure list.

14. Flat pack' flat woven bamboo bicycle concept (newatlas.com/bamboo-composite)
15. Bamboost flat woven bamboo e-bicycle concept (newatlas.com/bamboo-composite)
16. Woven bamboo tubes bicycle detail (motorcove.com/hero-bamboo-bike)
17. Woven bamboo tube construction detail (motorcove.com/hero-bamboo-bike)
18. Bambike Victoria Bolt laminated frame bicycle (bambike.com/victoria-bolt)
19. Bambike Estrella Bolt laminated frame bicycle (bambike.com/estrella-bolt)
20. ENSIETA 'Bamboo car' Eco-Shell 2007 (club-eco-marathon-shell-ensieta.blogspot)
21. University of Alabama recumbent bamboo trike (ASME) (Twitter)
22. Ajiro' reverse trike bamboo trike concept by Alexander Vittouris (velomobileseminar.com)
23. Alexander Vittouris riding the partial-fairing velomobile prototype (theage.com.au)
24. Lexus LS600h bamboo center console example (images.thecarconnection.com)
25. FIAT 500L Trekking 'Street Surf' bamboo side view mirror (blog.vehiclejar.com)
26. Rinspeed bamboo vehicle concept door step (arpem.com/rinspeed/bamboo)
27. Toyota ME.WE concept bamboo interior concept (greencardesign.com)
28. Phoenix concept by A. Birkner and K. Cobonpue (albrechtbirkner.com)
29. Phoenix concept interior by A. Birkner and K. Cobonpue (albrechtbirkner.com)
30. Bamboo electric buggy by Jörg Stamm (worldbamboo.net)
31. Wheelbase and track drawing (own property)
32. Bamboo culms on arrival (24th June 2017) (own property)
33. Front axle and longitudinal connection detail (own property)
34. Chassis base platform prepared (own property)
35. Chassis with diagonal, top and rear members (own property)
36. Bottom end of steering column (own property)
37. Pocket on one end of the steering column culm (own property)
38. Chassis with steering system and seat prepared (25th July 2017) (own property)
39. Front axle and longitudinal final covering detail (own property)
40. Front axle section with upright, swivel and wheel assembled in place (own property)
41. Measuring angles to position uprights in correct angle (own property)
42. Brake pedal detail (own property)
43. Front right corner detail (own property)
44. Pusher device top end (own property)
45. Pusher device bottom end (own property)
46. Set-up before set-down (own property)
47. Set-down ready for shake-down (3rd August 2017) (own property)
48. Season pictures on set-up bases (own property)
49. Track and speed records at Vitoria-Gasteiz ($6^{th}$ August 2017) (own property)
50. Track and speed records at Arroiabe second race ($9^{th}$ September 2017) (own property)

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