Eco-marathon racing car casing and frame structure design

Emese Kozák, Ádám Gégény, Ferenc Zombori, Sándor Forrai, István Péter Szabó
University of Szeged Faculty of Engineering
Moszkvai körút 9. HU6729 Szeged, Hungary
pszi@mk.u-szeged.hu

Abstract. In addition to the Pneumobil competition, our team will also participate in the Shell Eco-marathon with an electric-powered prototype category car. Based on our results so far, we are in the midfield of European competitions. After several modifications to our current car, we will be building a new car again in 2022. The goal of building eco-marathon racing cars is to achieve the lowest possible energy consumption, and accordingly, great emphasis should be placed on reducing weight and drag coefficient.

Our previous cars used a welded aluminum frame and fiberglass. One of the best ways of weight reduction would be a self-supporting, carbon-fiber composite frame structure; however, the team does not currently have the technology to produce this. The frame structure of the new car consists of carbon fiber composite tubes, the nodes are 3D printed, fiber-reinforced composite elements. The streamlined casing of the vehicle consists of vacuum formed PETG elements. By using this structure, the total weight can be radically reduced at minimal cost. In our publication, we describe the main steps in the design of the casing and frame structure, finite element analysis of air resistance and deformations, and the drive chain.

1. History of the Shell Eco-marathon competition
The Shell Eco-marathon is a global academic program, focused on energy optimization. It is one of the world’s leading student engineering competitions. Over the past 35 years, the program has consistently brought to life Shell’s mission of powering progress, by providing more and cleaner energy solutions. The global academic program brings together Science, Technology, Engineering and Maths (STEM) students from across the globe to design, build and operate some of the world’s most energy-efficient vehicles. All in the name of collaboration and innovation, as students’ bright ideas help to shape a lower carbon future for all. The competition dates back to 1939, when Bob Greenshields, Shell’s Research Director, made a friendly wager with his colleagues to see who could get the best fuel economy from road cars adapted to maximize energy efficiency. Bob achieved 49 MPG, setting a record, and creating a legacy that has lasted the distance.

The Shell Eco-marathon officially launched in 1985, when 25 teams gathered in France, to pit their wooden vehicles against one another, in a format that laid the foundations for the competition we now know and love.
The track competition has come a long way since then and today’s teams can choose from an array of energy options, from battery electric to hydrogen fuel cell, using different materials, from advanced carbon fiber to bamboo. In 2020 and 2021 with the cancellation of live events, the Shell Eco-marathon made the transition to a virtual program, resulting in great achievements, despite numerous odds. But one thing that hasn’t changed is Shell’s commitment to provide STEM students with a platform to collaborate and learn, to help shape a lower carbon world.

To date, more than 100,000 students from hundreds of universities in over 60 countries have participated and the legacy of the Shell Eco-marathon is clear to see. At these competitions one can meet the teams from previous and read their inspirational stories, with real-world impact on the STEM global community [1].

The general aim of the Shell Eco-marathon is to inspire teams of university students to build energy-efficient vehicles in various specified categories. Teams can design their vehicle in two categories: according to the specifications of a prototype or an urban concept. Within the two categories, vehicles with an electric or hydrogen-powered internal combustion engine can be built.

STECO – the team of the University of Szeged Faculty of Engineering enters the electrical category and has also taken part in the same category in previous years as well [2] [3] [4]. Although questions arise [5] [6], the spread of electric drive is becoming more and more intense today. An important advantage is the simplicity and low weight of an electric drive. The developments concern the control electronics of the electric motor.

The target is to build a vehicle that can run the longest distance possible by using the energy equivalent of 1 kilowatt hour.

2. Results of the team Szeged so far
The team of the University of Szeged Faculty of Engineering has been participating in the Eco-Marathon competitions in the electric-powered prototype vehicle category since 2015. Based on the results, the team is in the European mid-range. The best result of the team so far was 242 km/kWh at the 2017 Le Mans gala race, where this team earned the best Hungarian achievement in the competition.

Figure 1. STECO team, 2015
The membership of the team is almost the same as that of the Airrari Szeged pneumobile team. At the Techtogether competition, which is organized twice a year, the team can claim numerous successful achievements, special awards, and category victories under the name of Airrari-STECO. The team’s best result was the absolute first place of the 2018 GTE Techtogether competition.
3. Presentation of the racing car used from 2017 to the present

3.1. Frame structure
The frame of the car is a welded aluminum structure. The advantage of this was the simple manufacturing technology. Compared to the previous construction, it was possible to reduce the weight of the 2017 frame, while making the structure more rigid. The frame of the next car is designed to be much lighter with similar strength.

During the race, the car reaches an average speed of 25 km/h, rolling as smoothly as possible. The surface of the racetrack is smooth, good quality asphalt. For these reasons, a rigid suspension system is used.

3.2. Engine, drivetrain
The drivetrain consists of the following elements: electric motor - sprocket - chain - sprocket – a pair of wheels - freewheel. The ready-made, purchased elements of the drivetrain were selected in such a way that they have high-quality bearings, precise fitting, and careful design.

In 2017, the electric motor was a Maxon type with a nominal voltage of 48 V, a power of 250 W and an efficiency of 89% (at an operating speed of 3100 rpm).

The engine drives the rear wheel through a 180/22 chain drive with a transfer of 180/22. When choosing the type of chain, it was taken into account which chain the other teams use in the competition and which chain has sufficient tensile strength and the lowest possible weight. That is how the 04B chain, which is fortunately available in Hungary, was chosen.

3.3. Body
The body is a composite structure: polystyrene resin reinforced with fiberglass fabric. The body is not a load-bearing element, its only function is to reduce air resistance. To manufacture the body, the positive shape was created by cutting to size and gluing the polystyrene planes after printing the appropriate cross-sections.

![Figure 5. Manufacturing the positive shape of the body of the 2017 racing car](image)

The surface was coated with gypsum and after sanding and applying the mold release layer, the body was manufactured. In order to reduce weight, the body of the new car is manufactured with a different technology.

4. Rules for the body of the new vehicle
The designed vehicle must be built in accordance with the rules of the Shell Eco-marathon competition in order to participate in the event.

The 2021 regulation specifies that: the height of the vehicle must be less than 1000 mm; the rail gauge of the vehicle must be at least 500 mm; the quotient of the height and the width of the vehicle must be less than 1.25; the axle-base must be at least 1000 mm; the maximum width of the vehicle must not exceed 1300 mm; the maximum length of the vehicle must not exceed 3500 mm. There must be a distance of at least 100 mm between the pilot's leg and the nose of the vehicle [7].
The final shape of the car could be formed through several concepts (Figure 6). Significant and conspicuous changes were made compared to the current racing car. In contrast to the previous 2017 vehicle, all the 3 wheels of the new concept are located under the body, and the body of the new vehicle is provided with significantly larger rounding, as a result of this, the frontal area of the vehicle is reduced.

**Figure 6.** Comparison of the 2017 racing car and three new concepts: Version A, B, C, D.

In several steps, the version shown at the bottom of the figure was realized. The creation of this is described below.

**5. 3D scanning of the pilot**

Taking into account the requirements of the regulation, the vehicle must be designed to be the smallest and the most aerodynamic to embrace the pilot as much as possible. The best way to do this is to know the size of the pilot and build the chassis of the racing car by using this information. In order to achieve this, the design required a 3D 1:1 scale model of the pilot, around which the body could be designed.

A 3D scan was required to create the CAD model. The 3D scanning was performed with a scanner called Artec EVA Lite and its processing software called “Artec Studio” [8]. The pilot actually takes a “lying” position, in which they still know that they can drive, and then the scan takes place. After capturing the images, the program generates a 3D model, that can be converted into the CAD design programs.

Three shots were taken: two “full” shots and one with the head in high focus. Making these recordings barely took 5 minutes, with control accuracy. The number of errors associated with the particular recording in the processing software helped to verify the accuracy. This error number must be below 1 before processing the given point cloud. In this case, the recording is suitable for further work, if it is
above 1, then it must be recorded again. The next step is to join the recordings to the identified joint points (Figure 7).

![Figure 7. Joining the 3D recordings of the pilot](image1)

6. Making the 3D model of the vehicle’s body
On the x-y plane a sketch is made that represents the top view of the body (Figure 8). The driver’s inclusive sizes are made by guiding lines. The wheel position, the 500 mm gauge and the 1400 mm wheelbase are determined. The front wheel’s position is planned for the driver’s knee flexion. By comparison I made the lowest size wheelbase. In this case there are other things that matter, but the driver. In the engine compartment, there is the electric motor, the battery, the chain drive and the position of it.
The next step is a sketch on the y-z plane. It represents a side view of the vehicle. (Figure 9).

![Figure 8. Top view of the car body](image2)
When the sketch about the top and side view is finished on the x-y and z-y plane, the side view sketch is extruded by the „Extrude” command 800 mm long (the essence is to be longer than the full width, so it should be extruded further than 600 mm).

After all, by the Extrude command the top view is designated and extruded. The important thing about it is the extrusion is not a solid body extrusion, but also an engraving extrusion (on the designated sketch everything should be cut out). After the cut out we get a „capsule” shape with sharp edges. These sharp edges should be rounded as much as possible. For the rounding the „Fillet” command’s „Variable” option was used for rounding with radius changes. First the rounding was made in half of the body and mirrored for the y-z plane, so a symmetrical rounded body was created.

The body setup is finished so the cover of the wheels must be made. The wheel position is known. A work plane must set on the y-z plane. It should be moved 310 mm and a sketch should made about the front wheel’s cover.

The sketch is extruded as a solid body 300 mm long. (Figure 10)

For the perfect shape for the wheel cover, the „Loft” command was used and some thickening and tightening was made. For this command three planes were set at different heights and a sketch was made about the cross-section of the wheelbase. The Loft command’s „engraving” option is used for making the final shape of the cover (Figure 11).
The Loft command should be set as to cut the extruded body, not the car chassis. Then the front wheel cover should be mirrored at the y-z plane then the three pieces should be united. The windscreen is made by the „Split“ command. (It is only made for visual design because the cover is fully made by a transparent foil, which will be foiled then). The result can be seen on the figures (Figure 12, Figure 13, Figure 14).

Figure 11. Front wheel cover loft

Figure 12. Top view with the pilot

Figure 13. Side view with the pilot
7. Air resistance

For a better result in the race, all of the unnecessary weight must be removed and the air resistance must be minimized. Air resistance is important, because when the car begins to move the following happens. Drag force affects the car with a vectors that are the opposite of the car’s moving direction. The volume depends on the car’s frontal area (A), velocity (v), drag coefficient (cw) and the density of air (ρ).

If the body in the fluid domain is not a perpendicular surface to the velocity vectors, then the drag coefficients correct the correlation (1).

\[ F_e = \frac{\rho}{2} \cdot c_w \cdot A \cdot v^2 \]  

The correlation from the left to right is:

- \( F_e \): drag force
- \( \frac{\rho}{2} \): half of the air density
- \( c_w \): drag coefficient
- \( A \): frontal surface of the vehicle
- \( v \): vehicle’s velocity

Reducing the air resistance makes the car more efficient, the force needed for acceleration is lower and it can hold the needed velocity.

Air resistance is comprised of pressure and friction resistance.

The body’s shape is made to look like a shape of a drop. In this case the friction resistance takes a bigger role in the full air resistance. [10]

7.1. The affection forces to the body

A fluid domain affects the solid body during the flow – it is braking it. This force is influenced and created by the pressure-shear voltage distribution on the body surface and the flow path’s characteristics behind the vehicle.
A flow path is created behind every body inside the frictional loss-making fluid domain. At that place the pressure and velocity can be different to the undisturbed flow’s characteristics. In general, a greater flow path behind, will cause more forces to affect the body. [10]

7.2. Calculating the drag coefficient

It is a comparison value for describing shape forms and a(n) unidimensional number for measuring the force of air resistance. [9] The lower drag coefficient causes a better vehicle shape according to air resistance.

The simulations about it are made by the Ansys Computational Fluid Dynamics (CFD) software. The models are made by the Autodesk Inventor Professional CAD modelling software. The goal of the simulation is to determine the drag coefficient at 6.9 m/s velocity.

The software used during the simulation:
- Ansys SpaceClaim
- Ansys Fluent
- Autodesk Flow Design

For the first step, the import of the file into SpaceClaim must done. Here I made the preparation of the model for the simulation. I made an enclosure around the body. Then I made groups about the velocity inlet, pressure outlet and the walls.

Then we did the meshing. The maximum size was 0.5, while the minimum was 0.05, with a poly-hexacore shape, with 10 layers (poly-hexacore shape is handled easier by the software and the 10 layers provide more precise calculations).

![Figure 15. Layers around and under the car](image)

For the solution, the parameters must be set up. Because of the body being streamlined, it is hard to define the laminar-turbulent flow’s boundary. So, I used a(n) SST k-omega model. It is not resistant to these boundaries and the possible mesh failures. Then I set the magnitude of the velocity inlet. Other values were set that describe the car body, and I ran the simulation. For the drag coefficient we got 0.170.

On the body surface I determined the velocity magnitude as a result of the airflow. These values can be seen visual on the Figure 16.
The modification of the airflow is defined and displayed on the visual. These values show the changes of airflow, at the moment of the impact and the corresponding changes of the airflow. It also shows the car’s wind-shade (Figure 17).

As a comparison I made a simulation using Autodesk Flow Design, with the new „Jupiter“ car and our older „Zeus“ Eco-Marathon car. Here the Jupiter’s drag coefficient is 0.16, whereas Zeus’ drag coefficient is 0.3 (Figure 18).
Figure 18. Comparing the 2017 Zeus and 2022 Jupiter air resistance by Autodesk FlowDesign

Table 1. The results of the air resistance simulations of the variants are shown in Figure 5

|                      | „A“ version („Zeus“) | „B“ version | „C“ version | „D“ version („Jupiter“) |
|----------------------|----------------------|-------------|-------------|-------------------------|
| Drag force – $F_{\text{drag}}$ [N] | 3.361                | 0.574       | 0.579       | 0.497                   |
| Drag coefficient - $c_w$     | 0.3                  | 0.196       | 0.199       | 0.170                   |

The results of the study show that the air resistance of the new car is much more favorable.

8. Manufacturing technology

The body is made out of PETG plates using vacuum forming. The capacity of the forming machine cannot do the whole process for the entire body, so the chassis is divided to smaller pieces. The number of divided body sections is 10.

The working space of the machine is 1000x2000x2500 mm. Figure 16. shows the chassis division.

Figure 19. Sections of the car chassis

The model illustrates those solid bodies which will be on the forming desk. Different colors show the different areas of the chassis. White is the cockpit-door, red is the engine compartment door, blue is the bottom part that is fixed to the frame. The thin polycarbonate elements are assembled by riveting and attaching. The templates for the vacuum forming are made by MDF blocks and manufactured by CNC milling.
9. Frame

The chassis should be fixed to the frame via locking tabs, and the frame should be made according to this. The frame also provides the stiffness for the chassis. The vehicle’s height is defined by the chassis’ interior height.

After all the steering system and the wheel suspension must be made in the frame.

The front wheels’ steering angle must be set up, as it must not touch any element of the frame or chassis.

In the engine compartment has to have enough space provided to accommodate the chain-drive, electric motor, battery and other control elements.

The cockpit is isolated from the engine compartment by an aluminum plate.

The frame (by derogation from the previous years) made by composite tubes and 3D printed connection nodes which are strengthened by glass-fiber.

![Figure 20. Frame sideview](image1)

![Figure 21. Frame top view](image2)

The frame’s finite element analysis is done for acceleration, braking and turning loads.

10. Summary

During planning of the STECO team’s new vehicle our main goal was to reduce weight and air resistance. For a lower total weight, our aluminum construction is replaced by composite carbon-fiber tubes. The connecting nodes are made by 3D printed glass-fiber strengthened composite. Another weight reduction technology is the making of the chassis. The elements are made by PETG plates with the technology of vacuum forming.

The shape of the car is another important part. The goal during the planning was the lowest possible air resistance. For this optimization we examined three chassis versions. Using the results of an Ansys software, we chose the best version. In comparison the new chassis’ air resistance is much lower than the previous versions and the previous car.

The wheels and tires of the vehicles are the same type so these rolling resistance remains the same. The total weight is much lower for the new car. The conclusion is that the Jupiter can take a longer trip with the same amount of energy!
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