Ecole Centrale de Lyon – Car n°281
Engineering Design Report

Design overview

Our team Ecurie Piston Sport Auto from Ecole Centrale de Lyon (France) is competing in a Formula Student competition for the seventh consecutive time in 2021. Thanks to all this experience, the team decided to design and build ***Invictus***, a car capable of competing with top teams on dynamic events within a reasonable budget and drivability within the reach of an amateur pilot.

We structured the whole development of our vehicle using the V-model. Starting from general requirements, Formula Student Germany rules and time expectations at dynamic events (4.0 s at acceleration, 5.2s at dry skid-pad), we developed specifications for each system, ensuring that they interact correctly and achieve the vehicle's objectives seamlessly.

Figure 1: vehicle during a testing session

Then, following that phase of conception, the production of the parts started. Unitary validation of each part was done before proceeding to the integration and validation of the subsystems.

Finally the car was put together in order to confront its performances to the objectives announced. During the months preceding the competition, the testing phase takes place to find the optimal vehicle settings for each dynamic event and train our drivers.

All along, our design guideline was the following:

- **Reliability**: To complete the endurance, we focused on reducing risks of failures based on experience from the previous vehicles. Firstly, we arranged the rear cell systems to avoid overheating and contact of the electronic and hydraulic components as much as possible. We then dedicated more time to checking and validating systems and parts before assembly. On the other hand, we have perfected our track test protocol to isolate problems and optimise settings more quickly, in order to be in competition conditions for as long as possible.
- **Ergonomics**: Because performance on the track is directly dependent on the driver's ability, we put a strong emphasis on making a driver-friendly vehicle. Thus, significant weights were given to ergonomic variables in our technical choices.

The result is a 219 kg car with tubular steel space-frame chassis, powered by a four-cylinder internal combustion engine delivering 85 bhp through 13” tyres and sticking to the track with fine-tuned suspensions and aerodynamic appendices.

Vehicle dynamic & suspensions

Tyre choice

Although they are heavier than 10” tyres, 13” tyres showed better traction in our lap time simulations (especially in acceleration and braking) and therefore offer a better overall performance. In addition, the 13” wheel leaves more space for the upright, the brake disc, A-Arms and suspension rod. Continental C10 205/470 R13 were chosen because they were 20% lighter than the others for the same price and the same grip capability.

Suspension

In order to ensure a great performance and a great driver control of the vehicle, the whole suspension system was designed to make the compromise between extracting as much grip as possible from tyres, keeping aerodynamics features in good position and balancing the driving feeling for non-professional drivers.

First, a non-parallel and unequal A-arm architecture was designed through 2D & 3D softwares. This architecture made it possible to have the wanted camber variation in corners and the limited and coordinated movements of the roll centers. The A-arms were realized with aluminium parts and carbon tubes, assembled by a gluing process, the reliability of which was validated via tensile tests.

Since non-linear effects in damping threaten the feelings of the driver, rockers were designed to keep the motion ratio as constant as possible. To avoid compliances, the absorber assembly was placed perpendicular to the chassis longitudinal axis, and the push rods and dampers in the rocker plan.

Finally, our springs have been chosen with ride frequency targets and adjustments have been made during testing to satisfy general driver style. To respect the required travel course and to have the possibility to make damping settings, 4-way dampers Öhlins TTX25 mkII are used.

Concerning the anti-roll system, two U-bar systems were chosen for their easier integration to the front and the rear of the car. The total roll stiffness was calculated to keep aerodynamic features in their operating domain and stiffness distribution to have a neutral handling behavior in Skid-Pad event. Front and rear stiffnesses are adjustable by changing the lever arms stiffness for both bars. It makes it possible to change the vehicle's behavior towards oversteer or understeer to suit the driver's preference.

In order to take into account the differences from theoretical design to final parts due to manufacturing process precision, verifications (3D bench) and some adjustments through trials were performed to compensate for the differences observed.

Steering system

For performance during corners, we maximize lateral grip using a constant turn model, which calculates the optimum slip angles depending on tyre vertical load, leading to a target Ackerman percentage, which is reached with well-placed steering points.

For ergonomics and enhanced driving response, load cases were used in the design of the steering pivot to minimize compliance at the steering wheel. Caster angle and caster trail are specifically chosen to lower the torque, thus reducing muscular fatigue.

Wheels Assembly

Essential load cases (acceleration, braking and turn) were simulated using 3D-tolerancing and load simulation software MecaMaster. The overall resulting assembly reactions were used to simulate each manufactured component i.e. hubs, hub-carriers and the different configurations with respect to the brake calipers, the bearings and the suspension system ball joints.

The wheel assembly integrates the wheel-speed sensors within an upright bearing chamber. Oz 13" Magnesium rims were fitted in order to diminish the overall non-suspended mass and the overall z-inertia. Uprights and hubs were made from 7075 t6 Aluminium alloy in order to have a lightweight and strong structure yet simple to machine. A bearing locknut at the front and a tripod housing at the rear apply the preload on the X-configuration angular-contact ball bearings. A washer is placed between the hub and each bearing to avoid stress concentration.

Static camber angle can be modified by shims of the upper-hub-carrier side and toe can be set through adjustable rod lengths.

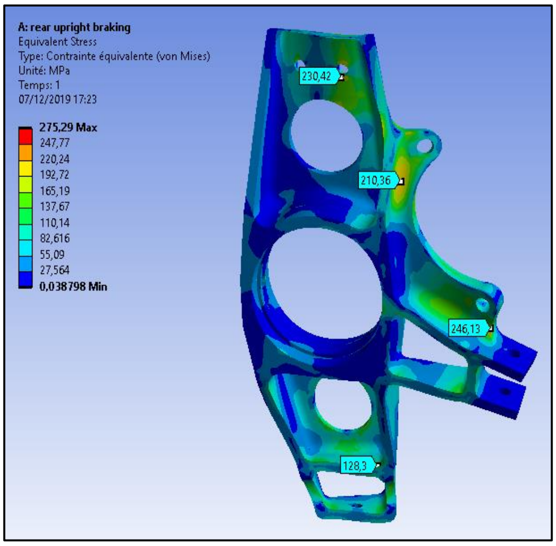


Figure 2:FEA of the hub-carrier

Braking system

The pedals have been designed to ensure reliability and good feedback according to pilots' feelings on previous cars. The current concept allows quick position adjustment to fit different driver height. We chose the parts of the brake system to reduce costs and mass, targeting an optimum braking distribution of 70% front. Thus, shorter brake discs were chosen for rear assembly, decreasing the overall mass of the brake system by 15% . Brake distribution is adjustable more precisely with a balance bar connecting the master cylinders. In order to shorten integration time and reduce risks of leakage, we chose to order crimped hoses.

Frame & body

Frame

To ensure reliability and strength, we chose a tubular space frame design using AISI 4130 steel with diameters going from 15mm to 30mm and width being either 1,5mm or 2mm. Our main focus was on increasing the stiffness/mass ratio, while securing proper implementation of all subsystems of the car. In addition, the frame was designed in order to enhance the suspension behaviour and the pilot's comfort. As a result, mountings of the rear suspension have been set to have linear phenomenon, leading to additional tubing.

The frame was analysed using finite element analysis built-in module in order to optimise the tubular structure. An iteration process between CAD and FEA helped us to obtain an architecture for the triangulation and tubing dimensions in order to both reach our mechanical objectives for the chassis as well as complying with the rules. The chassis stiffness (1400 Nm/deg) was set to be at least 4 times the suspensions' stiffness to avoid excessive distortion under high dynamic load. To have the desired suspension geometry as well as an easy engine integration, the car has removable bracings. The expected mechanical behaviour was verified with physical tests afterwards.

Figure 3: testing of the frame torsion stiffness

Body

In pursuance of the general guideline of the vehicle, the main objective of the body was to gain some weight without hindering aerodynamics. We chose not to add any side pods for weight and financial savings. As a result, we could afford the use of carbon fiber for the body. Carbon fiber side plates were also used to easily work inside the side impact structure while allowing us to gain some weight and aesthetic.

Ergonomics

Even though you have well-engineered vehicle dynamics, if the pilot does not feel comfortable or safe, the performance will shrink. This is why we decided to focus on the ergonomics for the pilot by different ways: we created fast-wooden prototype in scale 1:1 in order to feel the driver's comfort, we decided to place the headrest in the main hoop and foam for his back to sustain the pilot at the shoulder level. Harness points were chosen in order to avoid constriction or choking. Steering wheel axle was placed in such a way that the driver's wrists are strained as little as possible and he can apply torque the easiest way possible.

Aerodynamics

After several CFD simulations and benchmark of existing aerodynamic features, we were able to design an aerodynamic pack providing up to 330N of downforce and less than 160N of drag at 50 kph without increasing the overall budget too much. Thus allowing us to gain up to 10% more points on skid pad and auto cross and endurance events, but losing less than 5% points on the acceleration event, and therefore increase the overall amount of points on dynamic events.

Wings and endplates were made of carbon fiber reinforced polyester, providing the best compromise between rigidity, strength, mass and price compared to glass fiber. Mounting systems and ribs were made from light laser/water jet cut aluminium plates.

Engine & powertrain

Engine choice & tuning

Considering our global design objectives, the criteria for the engine was for reliability, the available power and torque, the mass and dimensions. Although we initially considered using light and compact mono-cylinder or two-cylinder engines, we finally chose to use a powerful four-cylinder that would guarantee satisfaction for any driver in terms of engine response.

The Honda CBR600RR engine was chosen because of its well-known reliability and its maximum power RPM which is lower than other models, meaning that the intake restrictor will have a lesser influence. In order to preserve its reliability, and easily accessible spare parts, we chose not to make major modifications to the engine. The original clutch was replaced by an anti-dribble one in order to cancel engine braking effects and allow clutch-less downshifting. We also conceived a new flat wet sump to lower the engine of 6 cm and consequently the vehicle's C.O.G. of 6 cm.

In order to increase powertrain reliability and performance, we spent time in testing. We chose to realize an engine mapping controlled by manifold pressure, which better reflects the air filling in the engine and is more reliable than the throttle position. We first adjusted the injection time map on a test bench to get a good response and make the throttle easier for the driver to appropriate. Then we adjusted ignition to maximise power, the goal was to reach 85hp with a minimum of 75hp between 9000 and 12000 rpm in order to reach lap time objectives. During testing sessions, driver feedback allowed us to adjust the transient speeds. Finally, the launch control has been set during testing sessions on track.

Figure 4: Engine tuning on a test bench

Exhaust & air intake systems

The intake and the exhaust systems were designed together to offer the maximum torque at 9000 rpm and to deliver a constant flow of power over a wide band of rpm (9000 to 12000 rpm) in order to ease drivability and maximise acceleration. The exhaust line has a 4-2-1 configuration and is made in stainless steel with a ceramic coating to lower the heat radiation, in order to allow a compact packaging.

The intake system was designed to reach our performance goal by optimizing the air flow between the four cylinders in order to have an equal filling and curb the pressure drop. The acoustic wave phenomenon in the tubings of the intake manifold was also taken into account in order to reach maximum filling at 9000 RPM. First, with straight tubings, and second, with the air flow entering the manifold correctly oriented, this design ensures an equal air-distribution between the four cylinders as well as minimal pressure drop. A non-conventional Venturi tube was also designed to fit the packaging specified by FS Rules.

Fuel system

A custom tank was created with a capacity of 6.1L, in order to be able to complete the whole endurance event. It was designed to ensure a constant fuel supply even in corners, using a buffer volume for the lowest point. A single fuel injector rail, kept in the original Honda location. One of the lightest fuel pumps available on the market supplies the injector rail.

Drivetrain

Several lap time simulations were made with different final drive ratios, we then chose the one that best met our scoring objectives. The use of only three gears is enough to take the best part of the engine's working range and to avoid frequent gear shifts. We use the original Honda gearbox (to comply with our reliability objectives).

The power transmission is achieved by a chain, which offers the best compromise reliability/performance. An adjustable limited slip differential has been chosen to improve traction during cornering and to limit understeering and tyre wear. The chain tension is adjusted with an eccentric system made in polymer (Delrin), which allows the whole differential to move longitudinally. The differential average position has been chosen to minimise tripod operating angle, taking into account wheel travel and chain tensioning. Steel axles have been selected for their strength and resilience.

Electrical

Electronic

The electrical system was created around a DTAFast ECU as its software is very user-friendly and allows us to use MAP/RPM injection and timing map with throttle transient. This ECU also has compensation depending upon water temperature and manages shift cut, launch control and traction control. The electrical systems around the ECU of the car have been separated in four different parts for reliability reasons:

- An electronic card positioned at the rear that allows the gearshift servo motor to be controlled and to communicate with the ECU. The gearshift operates in a closed loop to ensure optimal gear shifting. An auto mode for the acceleration event is also available to shift at optimal RPMs.
- Another electronic board is positioned at the front and manages the display of information for the driver, and instructions from the driver to the engine controller via the CAN bus (launch control, traction control, log, wet/dry mode).
- A data acquisition system which contains a RaceCapture MK3 data logger and a sensors.
- The main fuse box, located at the rear of the car, contains the relays and all the protective fuses for the rear harness. A second fuse box is located at the front of the car and contains all the protective fuses for the front systems. This choice was made in order to reduce the number of wires passing through the firewall. These two boxes are placed in such a way as to be easily accessible.

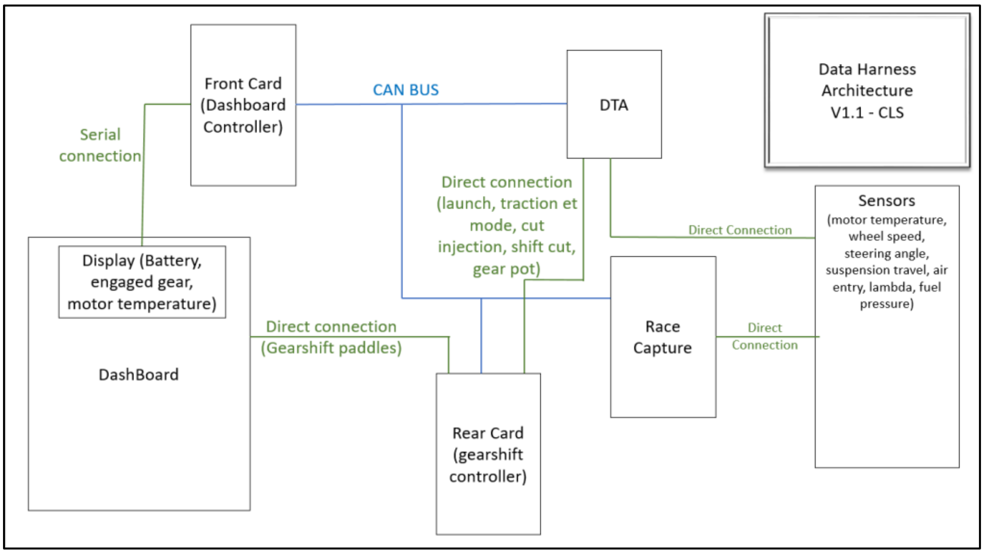


Figure 5: Data architecture of the vehicle

Electronic Cards

The electronic boards are based on a Teensy 3.2 whose dimensions allow direct integration on the printed circuit board. The result is a single electronic board which provides the same functions as an Arduino with stacked shields but saves space and weight. To reach reliability, it was decided to buy a micro-controller directly integrated into the board rather than buying the components separately, thus avoiding integration problems. Furthermore, the cards can still be removed for reuse.

Harness

All electrical elements are fuse-protected and follow standards for vibration and protection against the environment. All the wires have been sized to be as light as possible. A 3D model of the harness has been made in order to integrate it on the CAD model, thus allowing to identify integration and collision problems in advance. Then, it enabled us to print a flattened layout of the beam with the correct lengths for each branch, which facilitated the integration on the car. Once all the wires were laid out on the board and braided, we started the integration on the vehicle in order to cut the excess lengths of the wires and crimp the different connectors. Finally after testing all the functionalities, we covered the harness with a waterproof tape that protects the wires from the environment, giving a professional and clean electrical finish.

Dashboard

As far as the dashboard is concerned, the choice of a screen for the display allows all the useful information to be concentrated in one place and to adapt to the different use cases of the car. For example, when the car is on the engine bench, certain information such as RPMs are necessary, whereas in racing, the drivers prefer to have only the shift lights to know when they have to change gears.

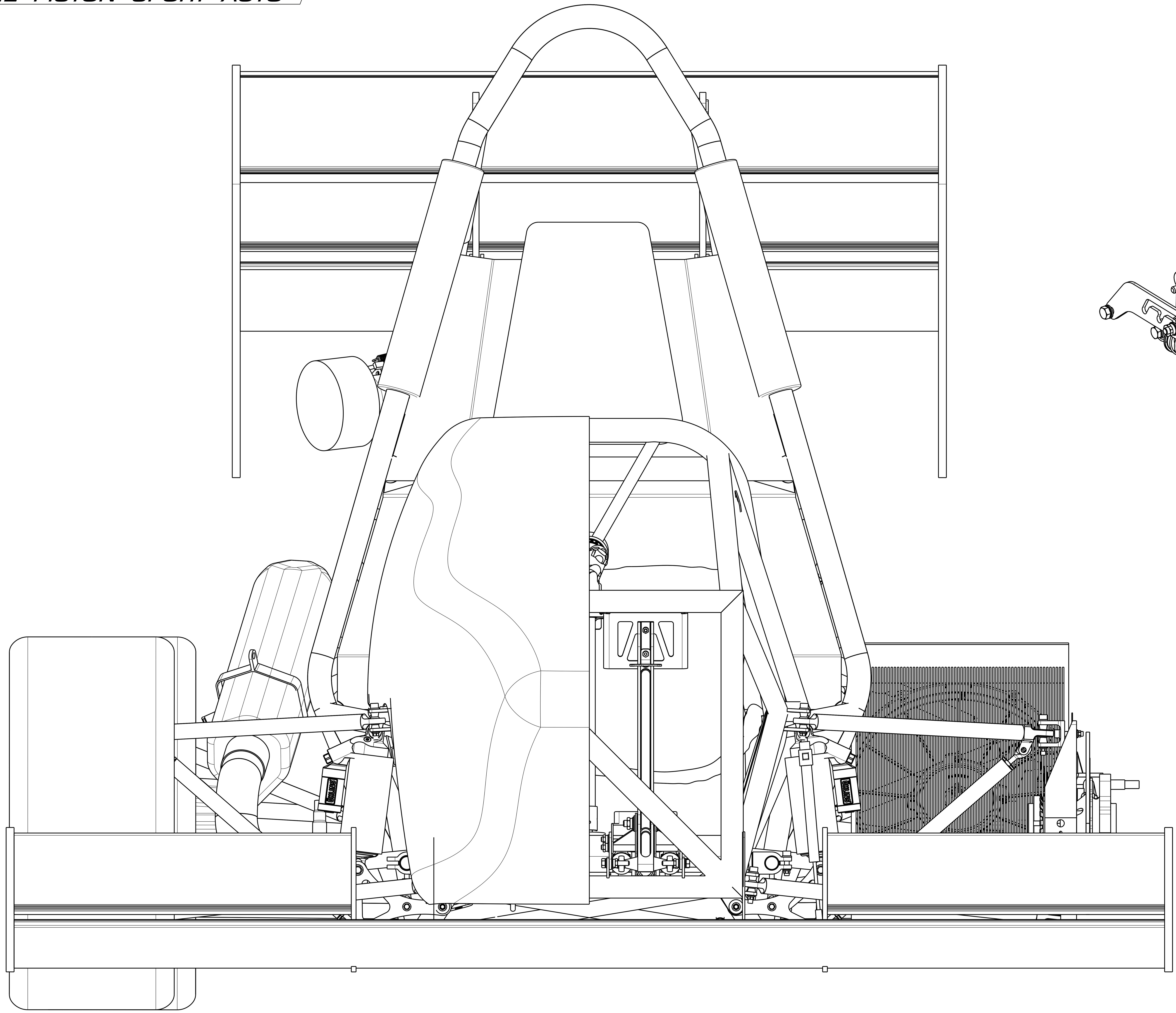
Data acquisition

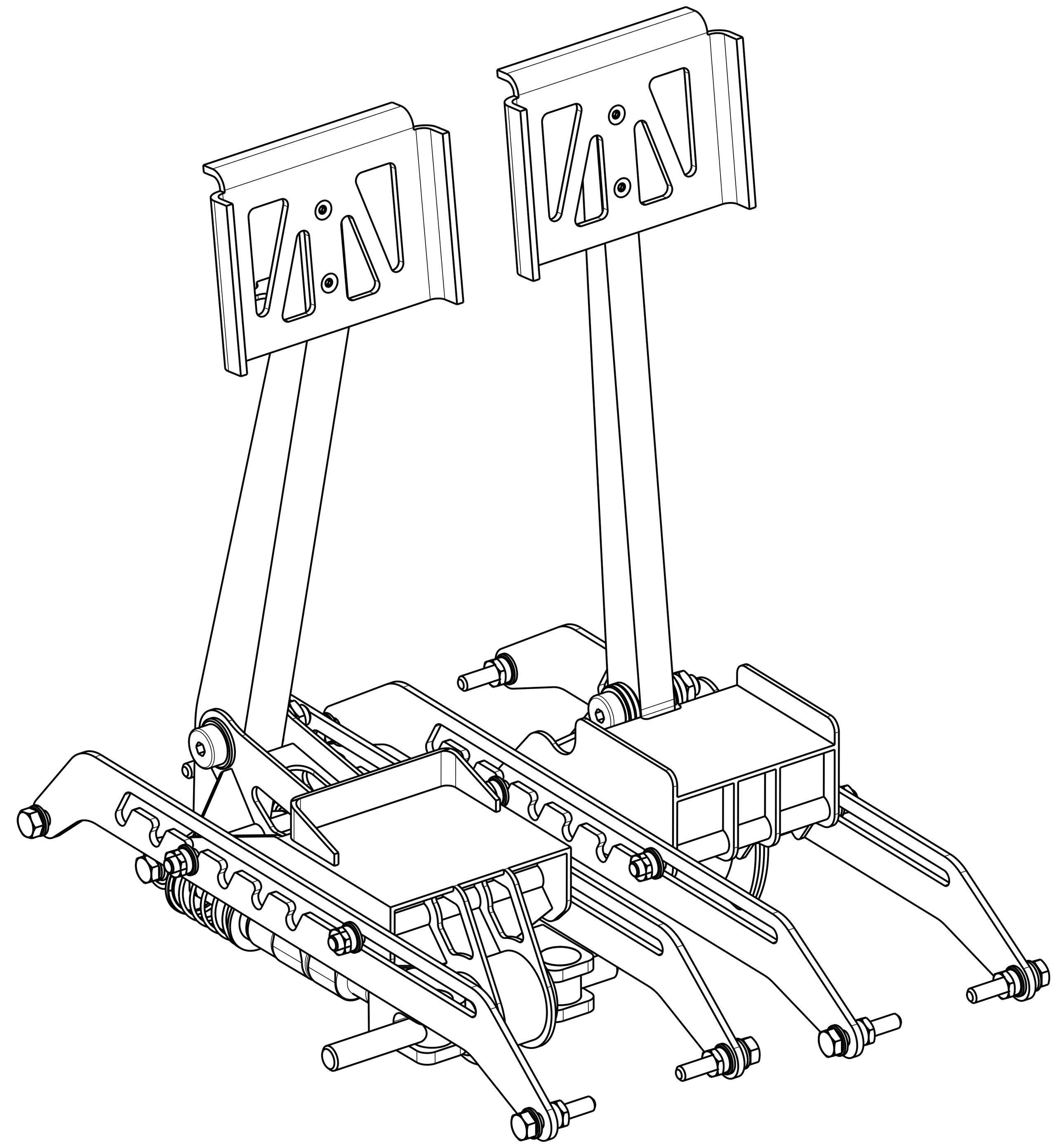
The central element of the data acquisition system is the racecapture MK3. We have chosen this logger due to the on board 6 axis Inertial Measurement Unit and GPS, its capability to read the CAN and its price.

A set of sensors to measure suspension travel, rack position which is an image of the steering wheel angle, brake system pressure, tyre and brake disc temperature are connected to the MK3, which will store all the data. In addition, a software supplied with the MK3 allows communication with the MK3 even when operating via Bluetooth or Wi-Fi.

These data can be analysed thanks to a Matlab application, which development started last year and has been continued during this season. Among other things, it helps with driver training and allows quick analysis during test sessions to make quick adjustments to the car.

EPSA
ECURIE PISTON SPORT AUTO





PEDAL ASSEMBLY

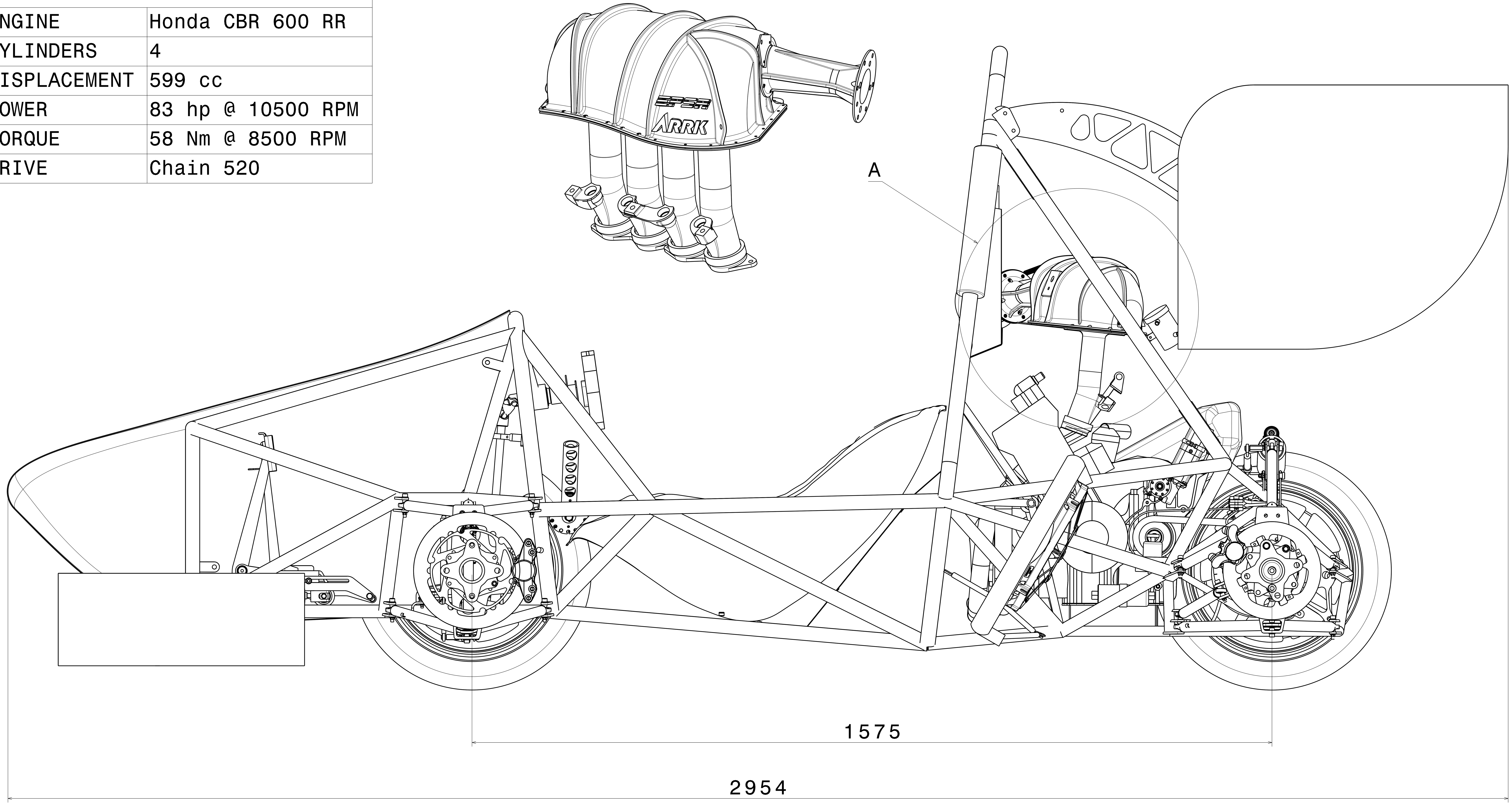
Design Report
Front view

INVICTUS

ÉCOLE
CENTRALE LYON

ENGINE & DRIVETRAIN	
ENGINE	Honda CBR 600 RR
CYLINDERS	4
DISPLACEMENT	599 cc
POWER	83 hp @ 10500 RPM
TORQUE	58 Nm @ 8500 RPM
DRIVE	Chain 520

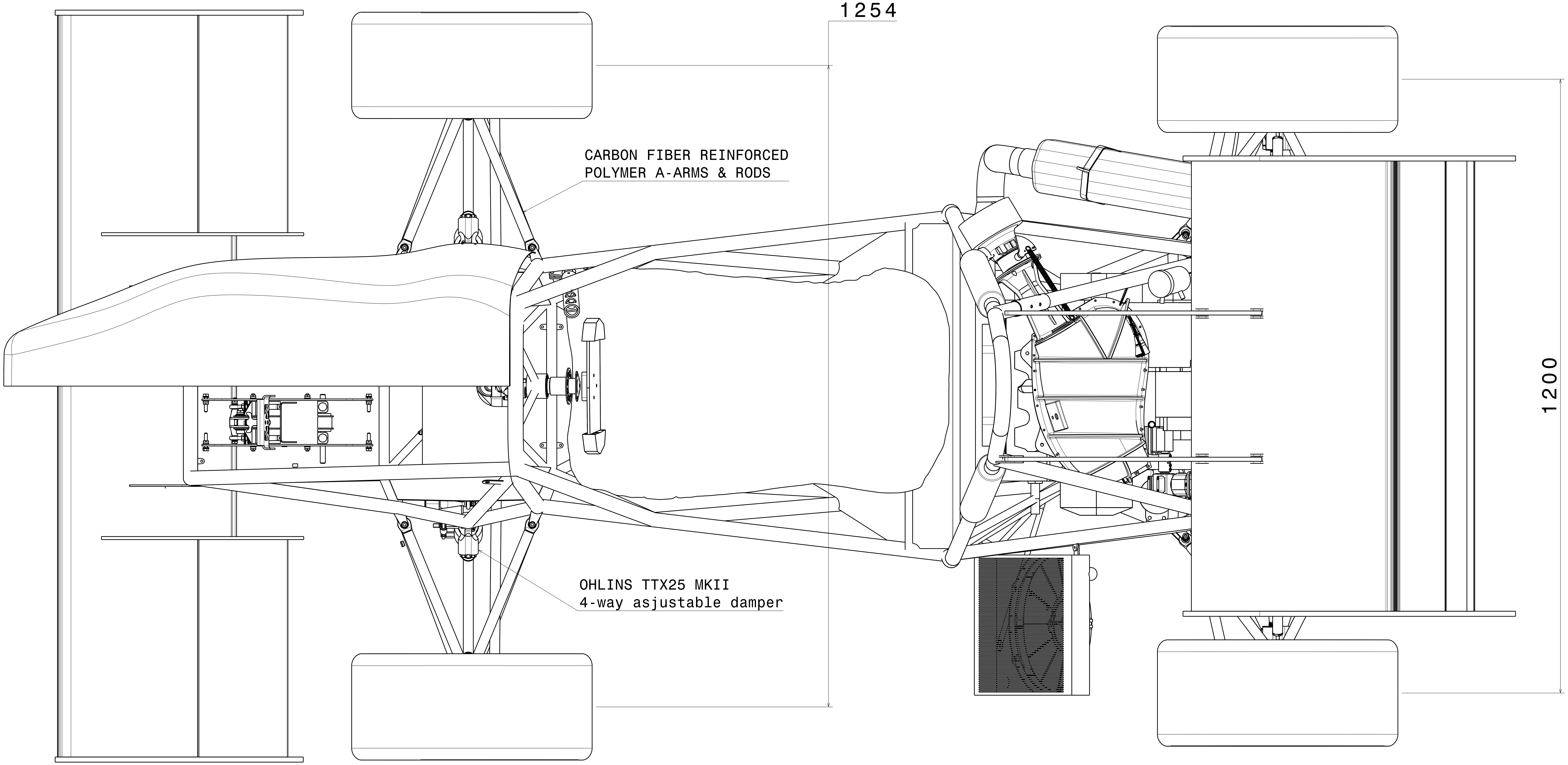
A - AIR INTAKE

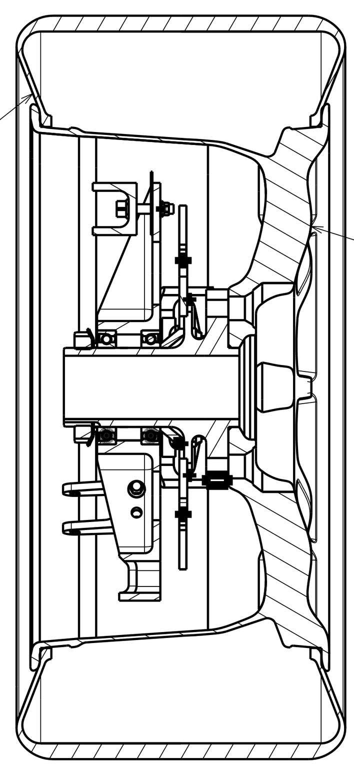


INVICTUS

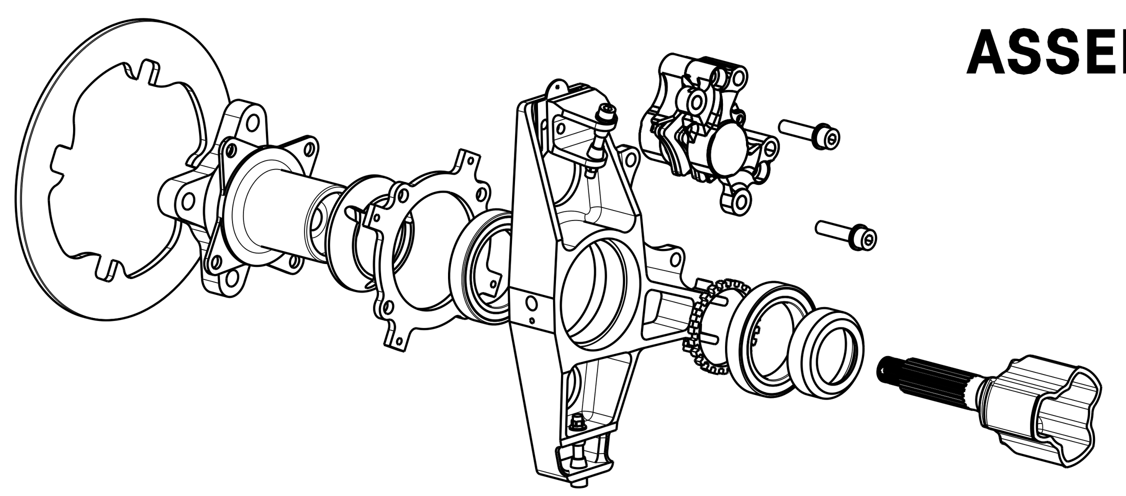
Design Report
Side View

ÉCOLE CENTRALE LYON





REAR WHEEL ASSEMBLY



REAR WHEEL ASSEMBLY

Design Report
Top view

INVICTUS

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