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Tiger 22 Design Report

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INTRODUCTION:

Clemson Formula SAE's 22nd vehicle, Tiger 22, is the product of a team design ideology focusing on vehicle subsystem integration over individualized optimization, creating performance that is greater than the sum of its parts. Over the last few years, the team has invested in this vision by developing simulation and modeling tools, as well as implementing a standardized design and documentation process. For 2020, the next step is to combine these tools into a unified design space to better understand critical subsystem interactions and build a platform for future development and innovation. This informs the following global design goals for Tiger 22:

Develop and utilize a trade space analysis to generate and evaluate vehicle concepts:

Trade space analysis is a method of mapping out and quantifying dependencies and interactions between subsystems and using computational methods to generate and evaluate potential design solutions. This system-wide approach focuses on integration to maximize global vehicle performance.

Achieve a wet vehicle weight (without driver) of 208 kilograms:

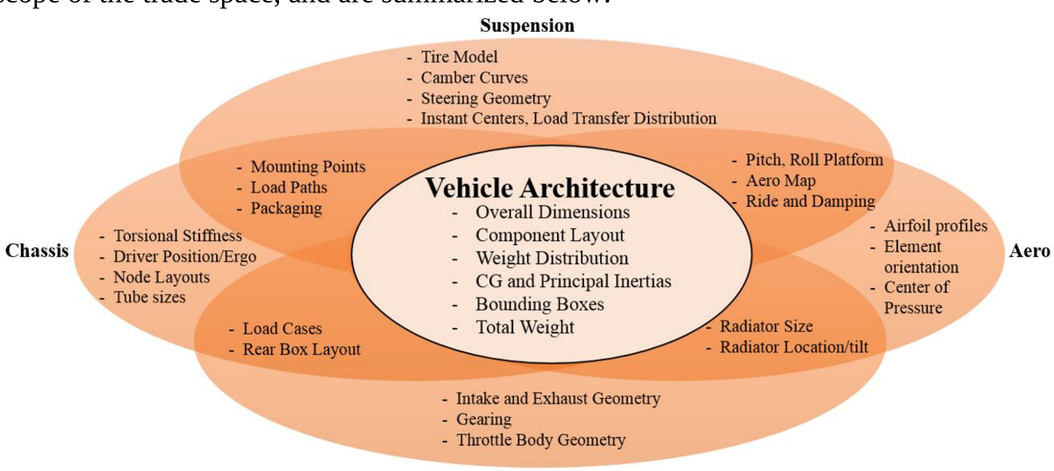
This goal is informed by lap time simulation results that demonstrate weight reduction is the most effective way to improve performance across all dynamic events. This target represents a 7 kg reduction, favoring sustainable long term improvements while retaining target compliance values in key components.

Focus on component design for time- and cost-efficient manufacturing:

Improved manufacturability enables faster vehicle completion and more time to test and validate critical simulations and design decisions. It is important that this is achieved without sacrificing function or performance. Thus, the focus is not to force simplicity, but rather to make informed decisions on what manufacturing processes to use, and then design components properly for those processes.

TRADE SPACE DEVELOPMENT AND ANALYSIS:

To set up the design space, the vehicle was split into four primary subsystems: aerodynamics, chassis, powertrain and suspension. From there, the team outlined subsystem interaction areas that had the greatest impact on global vehicle performance, and identified the parameters necessary to define those interactions. These combine to define the scope of the trade space, and are summarized below:



Vehicle Architecture

Vehicle architecture served as a higher-order centerpiece for the study to tie all of the subsystems together. This was captured using a parametric SolidWorks model that outputs subsystem bounding boxes and mass distribution properties for various vehicle layout configurations. This model is constrained by key packaging, ergonomic and rules constraints, allowing for a realistic exploration of the design space. A centralized environment was created in ModeFRONTIER to link the parametric model to other subsystem specific models, which then combine to generate a GGV-diagram-based lap time simulation that predicts vehicle trajectory and performance at 2019 FSAE Michigan dynamic event tracks. This setup allows changes in one subsystem to automatically propagate to the others, quantifying the dependencies between parameters and mapping out their effect on total vehicle performance.

Final concepts were synthesized using ModeFRONTIER's genetic optimization functionality, with a single objective: maximize points scored at dynamic events. To evaluate transient and stability effects, step-steer simulations and linearized control derivative calculations were carried out as supplementary analyses and considered alongside the optimization results. A short wheelbase and narrow track width (1537 mm/1117-1168 mm) significantly reduced lap times via the shorter trajectory taken through autocross courses, at only a minor penalty to steady-state performance and yaw damping. A 50/50 weight distribution was similarly selected to prioritize stability and response over the modest steady-state performance gain from a rearward weight bias. Lastly, the low load sensitivity of the R25B tire compound selected enabled a vehicle packaging layout that favored minimizing yaw inertia over center of gravity height. With vehicle architecture finalized, the next phase of the trade space analysis focused on the following subsystem interactions.

Suspension and Aero Platform:

Managing the motion of the vehicle platform is key to maintaining consistency of downforce and tire grip. Platform development began with preliminary CFD aero maps to predict center of pressure migration under pitch motion. These results were used to explore the effect of pitch stiffness on key stability and control metrics such as stability index and sideslip returning moment. With pitch, heave, and roll stiffness targets selected, various suspension concepts were compared based on achievable ranges and resolution of spring and damping rates. Ultimately, a pitch/roll decoupled suspension was selected. This concept contributes to the desired pitch stiffness independent of other modes, and enables pitch, roll, and heave to simultaneously have adequate adjustability and resolution near critical damping. This addresses previous vehicle issues where it was impossible to achieve the pitch and roll damping desired by drivers simultaneously. In addition, independent control of pitch and roll rates eliminated a degree of compromise when selecting kinematic instant center locations to control weight transfer.

To help improve the consistency of front wing performance, the pitch center of the vehicle was moved forward to 30% behind the front axle. Other options considered were raising the pitch center height by 72% which would increase vertical jacking forces while forcing sacrifices in chassis node placement and manufacturability, or increasing ride rates 15% and sacrificing damper adjustment resolution. To minimize undertray sensitivity to the increased range of motion in the rear suspension, the diffuser exit was placed in front of the rear suspension.

Aero and Powertrain Cooling:

Managing airflow for cooling was a balance between reducing cooling system weight and achieving high downforce with low drag. The cooling system was designed using the NTU effectiveness method of heat transfer and a MATLAB script that simulates running the car in the endurance event. The design goal was to find a combination of radiator core area, water pump, and fan selection that will sufficiently cool the car to complete the endurance event in 32°C ambient conditions, which will allow the car to compete reliably in hot environments. Physical data for coolant mass flow rate (MFR), engine heat output, radiator effectiveness, and air MFR across the radiator were obtained to calibrate the script. The script was then used to create an air MFR requirement vs radiator area curve. The initial MFR target was set to 1 kg/s at average track velocity, as higher rates yielded diminishing returns for weight savings from radiator sizing. Front wing concepts were tested in full car CFD to evaluate their effect on airflow to the radiator, represented by an empirically developed porous model. Outer endplates were added to the undertray, sealing away turbulent front tire wake and increasing air pressure to the radiator to boost air MFR. Initial iterations showed that the aerodynamic performance gains allowed from decreasing the MFR target to 0.75 kg/s outweighed the subsequent weight penalty incurred by a larger radiator, and the air flow design goal was adjusted accordingly. The final package achieves an average track speed air MFR of 0.76 kg/s.

Frame Packaging Integration:

When frame design is driven by other subsystem development, conflicting packaging requirements can lead to inefficient tube placement and added mass. To avoid this, subsystem designs were guided by their geometric interactions with the frame and nearby components. When suspension kinematic targets were selected, several control arm geometry concepts were iterated that achieved those characteristics while optimizing pickup point locations for minimized lateral roll center migration and suspension link loading. This catalog of solutions was submitted to chassis designers for evaluation and feedback, initiating an iterative loop to converge to a final concept that achieved kinematic targets while creating a stiff and easy to manufacture frame geometry.

Special attention was paid to the rear suspension box due to the added accessibility requirements for engine and drivetrain components. With input from all subsystems, various rear end concepts were generated and compared with decision matrices. The final concept shrinks the rear box, improving accessibility to the drivetrain and allowing for better differential adjustment kinematics. The smaller control arm base requires larger suspension links to achieve adequate stiffness, but overall vehicle weight is reduced due to subsequent reductions in the frame and differential mounts.

With vehicle architecture finalized, and crucial subsystem interactions characterized and addressed, the final stage of vehicle design was focused on optimizing subsystem-specific performance.

FRAME:

Chassis division development focused on utilizing automated design tools to achieve a subsystem wide 2.25 kg weight reduction and a target frame mass of 27 kg. A target torsional rigidity of 2000 Nm/deg was informed from SAE literature (ISSN: 0148-7191) and validated through previous vehicle tuning. Major topology decisions prioritized ergonomics and serviceability while maintaining mass and stiffness targets. Structural analysis was run with Altair's HyperWorks using 1D elements with 2D cross-sections in an FEA script. Automated scripting enabled optimization on the cockpit geometry and tube thicknesses rear of the main roll hoop using ModeFRONTIER, minimizing mass under torsional displacement and stress constraints. Inputs for the optimization are bound by packaging and rules compliance, and stress values are calculated from worst-case cornering, bending, and impact loads. Structural composite panels on the underside of the frame and structural engine mounting combine to increase torsional stiffness by 10 and 24 percent, respectively. These predictions align with previous physical testing results. The final frame has a simulated stiffness of 1950 Nm/deg at an estimated final weight of 27 kg.

COCKPIT AND CONTROLS:

Placing a greater focus on the usability and readability of the primary interfaces between driver and vehicle, Tiger22's dashboard was designed with HID best practice guidelines in mind. Through a combination of driver feedback from vehicle and ergonomic rig testing, a minimum display angle of 60 degrees relative to horizontal was selected. Care was taken to provide information redundancy on the display, switches, and tachometer, with both text and colors designating the data being communicated. Colors chosen to present data were selected to be clearly distinguishable to colorblind drivers. Ergonomic rig testing feedback was also used to locate switches and buttons on the dash, placing those that the driver may need to use while strapped into the harness in the most accessible locations.

A change to a single piece steering column reduces compliance with a minimal ergonomic tradeoff, supported by ergonomic rig testing feedback. For the column support, topology optimized steel plates are supported by bonded outer composite panels. These changes reduce overall steering mass by 1.5 kg. The steering wheel is a composite plate with 3D printed grips, and shifting is controlled through steering wheel mounted paddles. The clutch is actuated through a hand lever mounted on the steering column support, located to prioritize reliability and accessibility over actuation force. Finally, an aluminum pedal box accommodates all driver sizes with 25.4 mm of position adjustment. The brake pedal ratio of 6:1 is matched with measured application force values to balance lockup torque at high speeds with pressure resolution at low speeds. A transition to radially mounted ISR calipers yields a 0.73 kg weight reduction and improved mounting stiffness.

SUSPENSION:

Kinematic characteristic targets were selected abstractly using higher detail versions of the GGV lap simulation. High camber compensation rates favoring lateral over longitudinal acceleration performance yielded higher overall dynamic event points. Kingpin axis angles were reduced to improve consistency of both steer returning moment saturation and understeer gradient via steer-camber effects. Low roll centers were selected to minimize link loading and jacking forces, prioritizing spring elements to provide roll resistance.

The physical implementation of the pitch/roll decoupled suspension was achieved using pairs of steel rockers on welded bearing shafts – one rocker for roll and one for pitch. The pitch spring and damper are integrated in a single coilover assembly, while the roll elements are separated into a damper and blade-style adjustable anti-roll bar (ARB). This setup increases the range, resolution, and speed of roll stiffness adjustments, while eliminating the need for a complex bi-directional spring unit. Moving the ARB drop to the pitch rockers shifts the majority of loads transmitted through the pitch rocker. This reduces max torsion loads in the bearing shafts by over 30%, reducing weight and compliance.

All suspension components were designed for minimum weight while satisfying fatigue, buckling and compliance constraints. Cyclical and worst-case loads were developed using a steady-state truss approximation, and fatigue limits were set to over 10^6 cycles based on previous vehicle testing miles. Camber and toe compliance were modelled as spring elements to modify a canonical bicycle model with added roll degrees of freedom. Analysis was carried out with step-steer and frequency-response simulations, with special focus placed on response time and steering phase around typical on-center frequencies. Final targets of 0.375 deg/g and 0.25 deg/g of camber and toe compliance were selected, respectively, as a balance between diminishing returns for weight reduction and vehicle control.

AERO:

Aerodynamic design targets centered on maximizing downforce and achieving a target center of pressure 49% aft of the front axle to maintain a consistent cornering gradient. Lap simulation sensitivity studies comparing ranges of lift and drag found that more aggressive packages yielded higher overall performance despite their low efficiency. Thus, minimizing drag was maintained as a secondary criteria to maximizing downforce.

The front and rear wings were designed using parametric optimization of 2D fixed airfoil placement, followed by verification in 3D full car CFD. The front wing was split into three mirrored zones to best maximize downforce within regulatory bounding boxes. Three element designs on the outboard portions of the wing yielded similar downforce values to higher element count configurations at a lower drag penalty. A simpler-to-manufacture front wing design that produces more downforce on its own was chosen over a more complex design that would push more air to the undertray, to provide more consistent performance and easier manufacturability. The rear wing features a two-element beam wing that sits forward of the three main airfoils for increased downforce at the rear. Swan neck mounts allow more undisturbed air to reach the bottom of the airfoils, creating more attached flow and improving performance. A slotted front wing mounting solution allows for rapid mounting and dismounting. The undertray utilizes an airfoil arrangement that underwent the same parametric design process as the wings. To achieve the target center of pressure, a set of nose wings were added above the front suspension to redirect air to the rear wing, increasing performance. Even though the nose wings create lift on their own, the net downforce gain is more drag-efficient than using a more aggressive rear wing to achieve the same balance.

The manufacturing process consists of unidirectional and plainweave prepreg carbon fiber wrapped around CNC milled low-density 31-IGF Rohacell foam airfoil cores, allowing relatively high airfoil volume with low weight. This strategy also allows complex contours in the Rohacell pieces with minimal added manufacturing complexity. Two-dimensional endplates are manufactured with prepreg and honeycomb core, and waterjet to the exact profile desired. Body panels are made of fiberglass, which allows for a light, sturdy, and cost-effective solution that is easily removable and replaceable.

POWERTRAIN:

For Tiger 22, the powertrain package continues to utilize the Honda CBR600RR. This is due to historic performance, an extensive knowledge of the platform, stock of compatible components, and the prohibitive effort needed to redesign for a different engine. Updates to the powertrain package for 2020 focus on improving the consistency of engine lubrication and optimizing the throttle body design for drivability and power.

Intake and Exhaust:

Intake and exhaust geometry design focused on higher-rpm peak power to improve acceleration and drivability. This design direction is supported by lap simulation results, as well as driver feedback during testing. Geometries were originally determined in an iterative Ricardo Wave 1D engine simulation, investigating pipe diameter, length, taper, staggering of lengths, and different collector configurations (i.e. 4-2-1 or 4-1). This model was first developed in 2016 and refined using steady-state torque values from an in-house water brake engine dyno to calibrate and validate key parameters. After initial dyno and in-car testing, it became evident that these gains stagnated for peak power targets above 10,500 rpm. Having found the saturation point for high rpm power, the intake and exhaust were restored to a proven geometry for power and reliability. 304 Stainless was chosen as the exhaust material due to its high strength at high temperatures and its weldability. The intake is made using a carbon fiber plenum with carbon-reinforced nylon runners, combining the stiffness of the carbon and the manufacturing flexibility of printed nylon in a lightweight package.

Oil System:

To avoid oil starvation in corners as well as premature oil overheating and degradation due to aeration from contact with rotating components of the engine, the Tiger 22 oil system was switched from a baffled wet sump to a dry sump. A dual-stage scavenge pump was selected as it offers the ability to have pickups on opposite sides of the oil pan while fitting within our packaging requirements. An air/oil separator was also added to minimize the effects of oil frothing. The oil pan was designed to minimize weight, reduce height, and ensure oil pickup during worst-case acceleration. The system oil capacity and tank size calculations conservatively assumed a maximum vehicle acceleration of 2.5 g and accounted for the operating rpm, thermal expansion of the oil, and volume of oil lines.

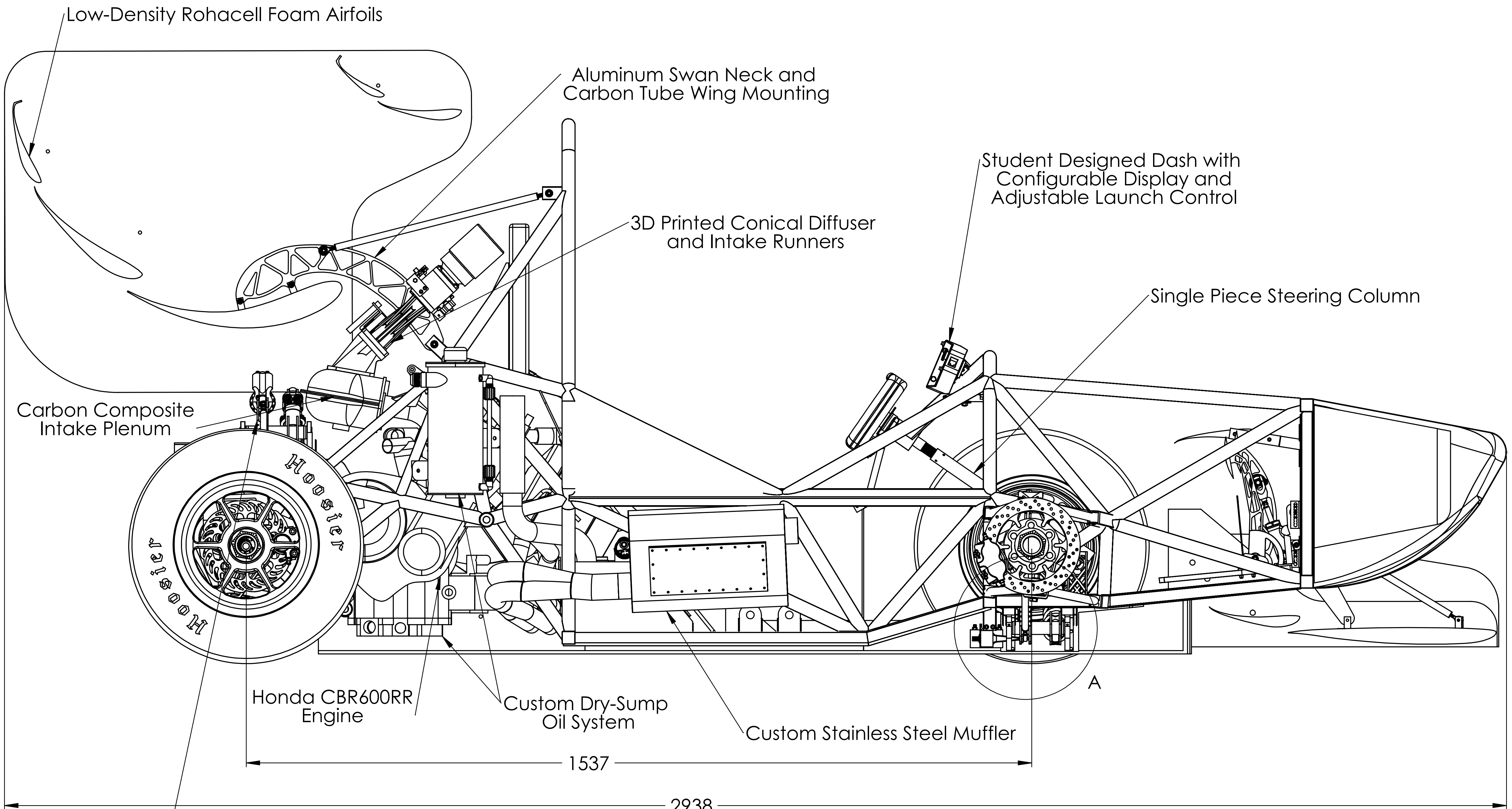
Throttle Body:

The throttle body was redesigned to maximize both throttle resolution and MFR of air through the restrictor. Both barrel and butterfly valve throttles were analyzed, with a barrel being chosen for superior drivability and manufacturability. Throttle diameters from 24-32 mm were tested using a 3D model in Ansys FLUENT, with MFR vs. throttle position curves correlating with measured flow bench data. The results were analyzed using a MATLAB script to predict the amount of time spent at each throttle position on an autocross track, giving a direct view of the range of throttle positions that would be used for a given diameter. Using that information as well as MFR at WOT, a 32 mm diameter was selected, having the widest range of usable throttle and minimal losses at WOT. After the throttle body is a removable conical diffuser, with geometry selected based on the work in *Applied Fluid Dynamics* by Robert D. Blevins to offer maximum pressure recovery. A modular design enables iterative testing to determine the most effective geometry, and it is sealed to the throttle body via a rubber O-ring, making assembly quick and simple.

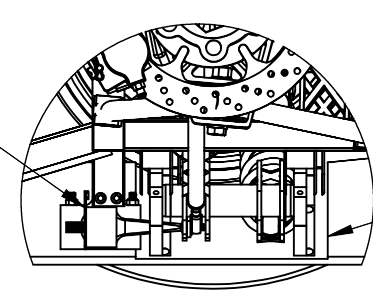
SYSTEMS MANAGEMENT:

With the increased focus on modeling and the addition of new complex systems across the car, efficient testing and data collection is a high priority. To that end, the reliability and serviceability of the electrical systems on the car was the primary focus during their design. The power distribution module features a two PCB design, allowing the low maintenance ground plane to be placed near the battery to reduce the length of wire, while the PCB responsible for the switching signal and fuses was placed in an accessible location on the side of the vehicle. OEM relays were selected for their vibration resistance and serviceability. The dashboard used on the car can display information collected by the data logger. Custom screens can be developed for specific tests, improving operational efficiency. Additionally, drivers have access to key data related to the safety of the engine, increasing overall vehicle reliability.

A secondary goal in designing the electrical system was achieving weight reduction through better packaging of components and more intuitive routing of wires. The wiring harness now runs along one side of the vehicle, with branches crossing the car only where necessary, thereby decreasing the overall length of wire and improving accessibility. Where possible, components share housings in order to reduce the overall footprint of the electrical system and decrease weight. Examples of this include the ECU, battery, and ground plane all sharing one housing, and the dashboard, power switches, and the ECU connection to a laptop all packaged together.



Pitch/Roll Decoupled Suspension with Custom Adjustable Anti-Roll Bars



Splitter Acts as Suspension Housing

DETAIL A
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CLEMSON FORMULA SAE

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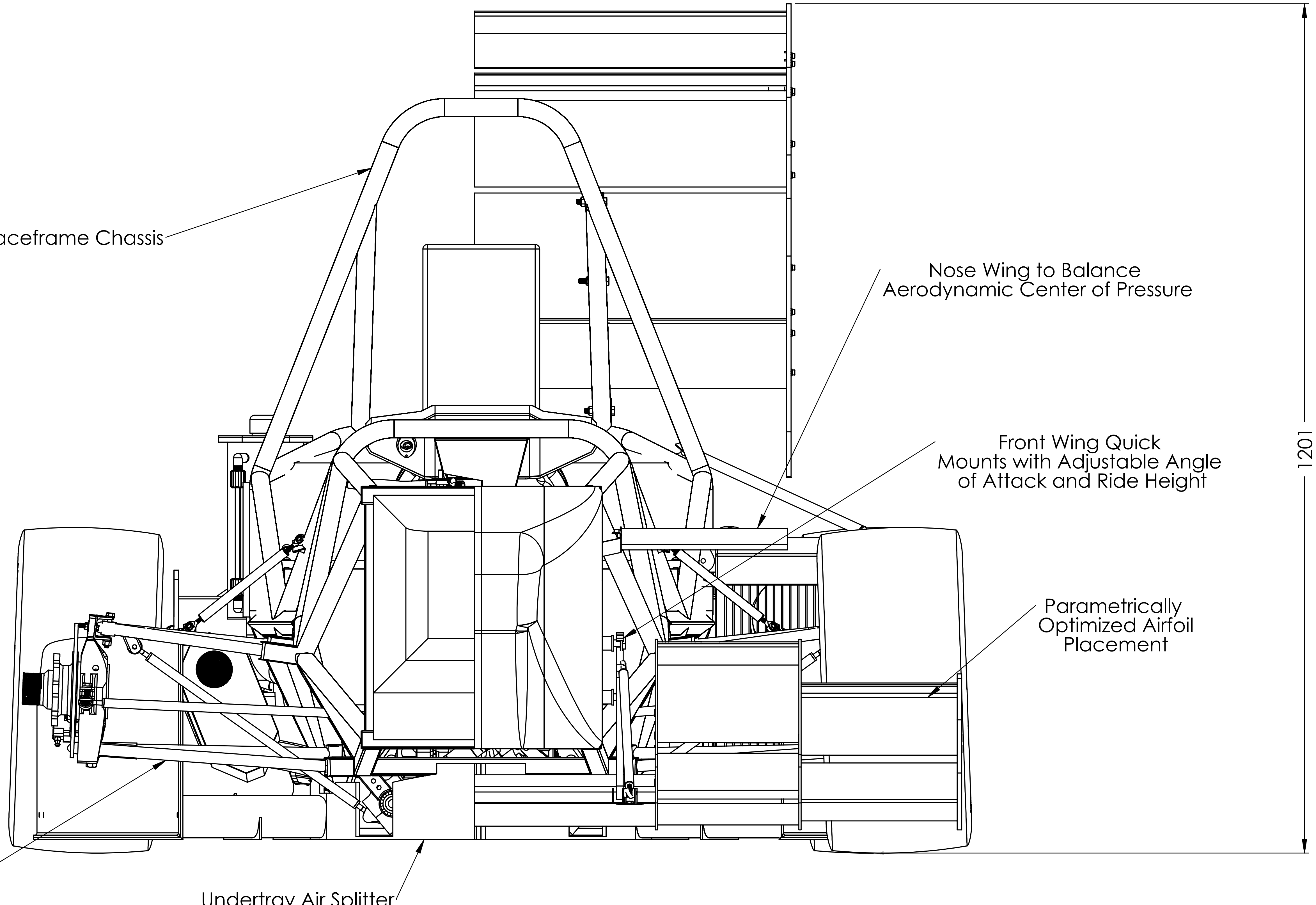

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CLEMSON FORMULA SAE

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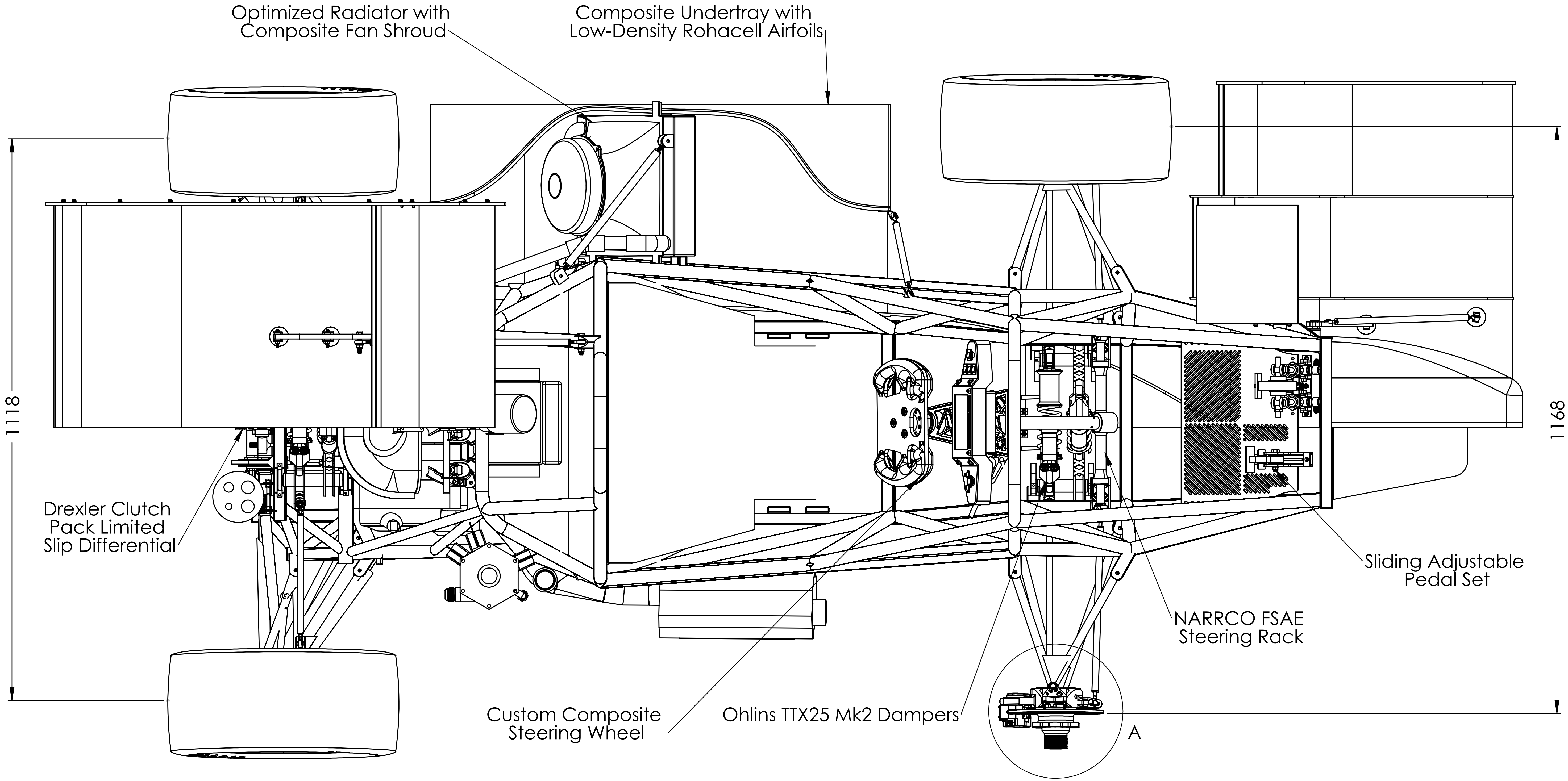

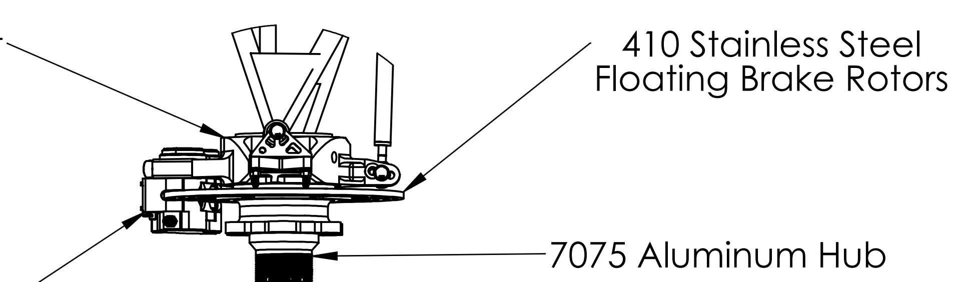

DETAIL A
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