Formula Hybrid+Electric 2024 Design Report
Worcester Polytechnic Institute
Goat Fast Racing
#204

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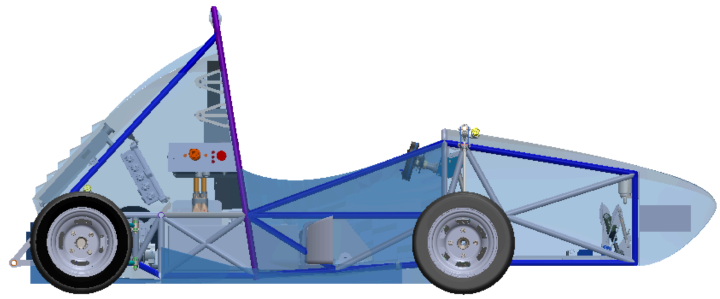
Overview



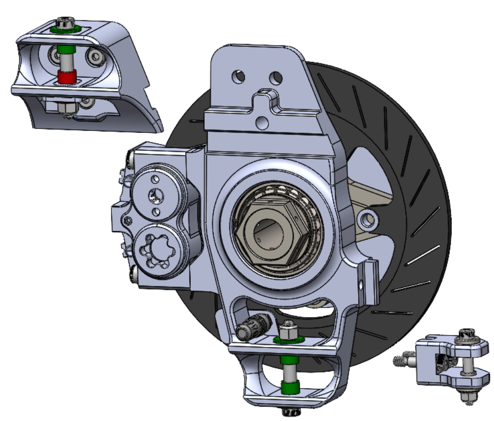
Coming into the 2024 season, we knew one thing: we wanted to make the highest performance car in WPI FSAE history. For us, that meant a few things. First, a system wide focus on reliability. Raw speed is nothing if you can't finish a lap. Second, a fully integrated car. Designing core parts of the car in isolation from one another makes comprehensive design optimization, and our performance goals, unachievable. The electrical systems, such as energy storage, powertrain, and control systems, had to be designed in from the start. Third, a car that's performant and fun to drive. From reducing driver steering effort to maximizing suspension performance in high cornering loads to improving ergonomics, we have done everything we can to make a car that is fantastic to drive. Finally, we knew that at the end of the year, we wanted to look at our car and feel completely satisfied with the craftsmanship and aesthetic value. That means full bodywork and extreme attention to detail in every subsystem of the car.

Wheel Packages

We began the concept of our car with the tires, moving inwards as the design progressed. From the start, we had three primary goals that affected our wheel package design. First, we wanted to sustain 1.7 G lateral and 1.5 G longitudinal loads. We chose these numbers because they represent a marked performance increase over our previous electric car, and are similar to measured loads on our team's past successful ICE cars. Second, we wanted to minimize steering effort, allowing our drivers to maintain precise inputs throughout the endurance event. Finally, we wanted to allow for as much adjustability as possible to tweak parameters after on-track testing.

To meet our first goal, we chose to use 10" Braid wheels and 16in Hoosier 43075LC0 tires to minimize rotational and unsprung mass. Additionally, Hoosier's softest LC0 compound is only offered in a 10" tire. The LC0 tires have a high coefficient of friction of up to 1.6.The performance increase of this wheel and tire comes at the expense of difficulty in packaging the uprights, brake calipers, rotors, steering arms, and toe rods. Our tire data analysis suggested that to maximize lateral loads, we should implement parallel steering and maintain low camber angles through steering.

We developed our uprights to maximize performance while still allowing for rapid adjustment. They incorporate RCV wheel hubs chosen for their compact size and high strength to weight ratio. Initial values for scrub radius, kingpin inclination, camber, and caster were established from the tire data and parameter optimization. Our front uprights were designed to accommodate a modular toe mount and upper control arm attachment point so that all parameters are adjustable with minimal additional machining. The upper control arm module interlocks with the upright body using a mortise and tenon style groove, shown at the top of the image to the right. This connection transfers longitudinal and vertical loads directly into the aluminum upright body, eliminating shear forces in the bolts. The toe mount uses a similar joint to transfer the



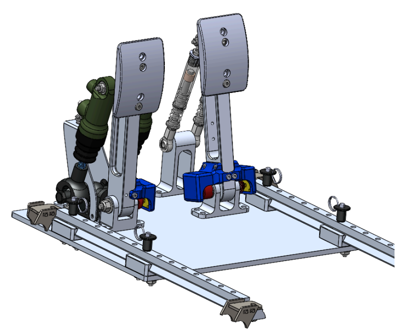
steering load. Both the front and rear uprights utilize camber blocks. They are placed on the upper mounting point and allow for tuning of camber in +/- .5° increments by replacing them with a different block.

A major goal of the rear wheel package was to minimize compliance and eliminate bump steer. To achieve this, we centered the toe mount between the upper and lower points, allowing for maximal toe arm length. This reduces the effect of backlash in the bolted connections and force caused by moments about the vertical axis of the tire. After extensive FEA on the upright assemblies, we achieved a minimum safety factor of 1.3 under extreme test conditions which are only possible in perfect tire conditions.

All four wheel packages include a custom sensor PCB that measures wheel speed based on changes in magnetic flux density and a non-contact IR sensor to measure rotor temperature. They are thermally coupled to the body of the upright to keep all components onboard inside their operating temperature window.

Brakes and Steering

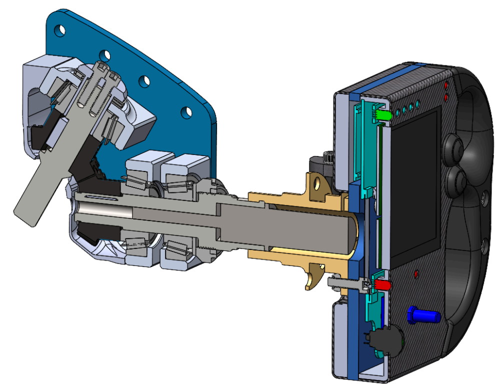
The braking system design was guided by three goals; the ability to lock all four wheels, quick adjustment for different drivers, and a compact pedal package. To minimize wasted space, we designed a custom brake pedal and balance bar mount. We are using Tilton 78-Series Master Cylinders due to their compact and lightweight construction, as well as the built-in spherical bearings that eliminate side loads on the piston. The Tilton 900 series balance bar was chosen for its ease of mounting and integration with the chosen master cylinders. The custom brake pivot allows the master cylinders to be mounted in an upside-down vertical configuration that minimizes the footprint of the components. When the pedal is fully pressed, the pedal pad is the furthest forward component, meaning no longitudinal space was wasted in the design. These choices resulted in a motion ratio of ~4:1, while this value is slightly lower than ideal, it is sufficient for an average drive to generate wheel lockable force.



To allow rapid adjustability while maintaining high strength, the pedal plate rides on two dovetail rails. Quick release pins are used to lock the pedal plate in eight positions spaced at 1” increments. The pedal package as well as custom accelerator, and pedal position sensors are shown on the right.

Force calculations to determine master cylinder bore size were based on vehicle mass, tire friction coefficient, rotor diameter, and the chosen brake calipers. The rotor diameter was set at 7.5” to maximize heat dissipation and clamping torque while leaving clearance between the calipers and wheels. The rotors were cut out of G-2 Cast Iron, a material chosen based on its performance in thermal simulations, and resistance to thermal fatigue. ISR 4 piston calipers were chosen for the front and 2 piston for the rear, due to their small size and ease of mounting. A mix of braided stainless brake lines and hard lines were chosen to maintain flexibility near the wheels and adjustable pedal box, as well as rigidity on long runs down the frame.

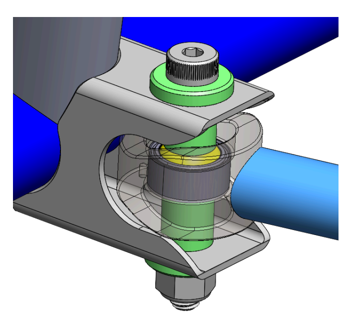
We designed the steering system to be adjustable for different drivers, have minimal compliance, and have a less than 11 foot turning radius. The turning radius was deemed a good target after modeling a racing line through a rules specified minimum radius hairpin. The Kaz FSAE rack was chosen due to its ample travel, minimal backlash, and ease of system integration. We chose to position the rack forward of the virtual front axle such that while turning, the outside tie rod is loaded in tension, allowing for the use of a lighter tie rod while minimizing system compliance. We designed a custom gearbox with two driver positions. The gearbox uses a set of 120° angled miter gears supported by tapered roller and needle thrust bearings. A cross section of the gearbox can be viewed to the right. Each shaft has a preload adjustment to fully engage the races and rollers. This bearing preload eliminates non-axial motion caused by driver induced side loads. This design allows for quick disassembly while maintaining tight tolerances which result in less than 1° of backlash in the gearbox. A custom steering wheel was also developed with a multitude of switches, LEDs, and a display to show driving data and facilitate tuning decisions.



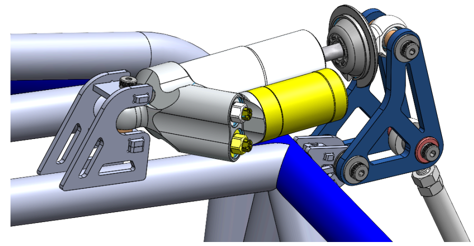
Suspension

The suspension design began in the wheel packaging assemblies. We analyzed previous car performance and defined desirable values for caster, kingpin inclination, and scrub radius. This year, we increased our kingpin inclination angle to reduce scrub radius and steering effort. We positioned the wheel packages to minimize our wheelbase while maintaining a stable track width (around 75% of the wheelbase in the rear and 80% in the front). The front and rear track width discrepancies allow for marginally reduced rear weight while minimizing front-end lateral load transfer. This discrepancy also makes navigating a tight course easier on the driver as the car will be less prone to understeer, which can be caused by an imbalance of lateral load transfer between the front and rear tires. Lateral load transfer has a net loss on traction and since track width is the denominator of the equation, a larger track width will decrease the load transfer. Implementing a larger track width at the front of the car allows a better chance at adequate front-end traction. Camber gain, toe change, and motion ratios through the 2” suspension travel were chosen to maximize contact patch area and relative tire angle. We used Optimum K, a widely used vehicle dynamics software package, to hone in on our desired parameters. Through numerous optimizations, we were able to achieve virtually zero bump steer, 0.8 degrees of camber gain per degree of roll, and an average motion ratio of 1:1 in the front and rear. A graph to the right depicts the outcome of a motion ratio optimization.

Using the OptimumK Forces Module, we generated expected forces at every suspension interaction point. These were based on tire data, longitudinal and lateral G force predictions, CG height, expected downforce, weight, and weight balance. With these values, we analyzed all control arms as well as the frame tabs and bolted connections using SOLIDWORKS FEA. Through this analysis, we were able to optimize the strength-to-weight ratio of all suspension components. One area for improvement over our previous cars had been the ease of suspension assembly. This year we implemented steel “Top Hat” spacers at every suspension interaction point. These spacers allow for external assembly when the control arm has already been positioned, eliminating the need to precariously position internal spacers. They also allow for micro tolerance adjustments to the fit of the shoulder bolt as well as the frame tabs. An example of a Top Hat can be seen to the right (the neon green parts) at an interaction between a control arm spherical bearing and a frame tab.



We chose an in-plane pushrod configuration for the dampers and rockers. The resulting in-plane forces allowed for the use of lightweight rockers. Bronze bushings at the pivots allow for smooth articulation while thrust bearings eliminate potential binding from the shoulder bolt torque. For dampers, we opted to use Öhlins TTX 25 MKII. These dampers use a hybrid twin tube configuration with a piggyback reservoir, are four way adjustable, and have an optimum travel range for our desired motion ratio and amount of travel. We oriented our dampers horizontally, with the cavitation-preventing nitrogen charged piggyback reservoir outside of the driver's direct line of sight



Chassis and Cockpit

Our goals in designing our chassis and cockpit are as follows: comfortable operation by a wide range of drivers, an optimized design for the expected loads with short load paths, and a balanced weight distribution with the lowest possible CG height. Above all, our driver must be protected from the electrical system and collisions.

To ensure driver comfort regardless of size, we created a configurable driver model to supplement models of Percy and the rules templates. We selected a reclined position to allow for improved packaging of our accumulator while placing the driver's hands and feet in ergonomic positions. We designed a removable frame member at the base of the main hoop, integral to the accumulator mount. The removable member allowed for high chassis stiffness while allowing the accumulator to be moved farther forward than otherwise possible. This design choice allowed us to minimize our wheelbase, which we expect will help improve our autocross times. Numerous driver mockups were created and tested to ensure drivers had sufficient hand and leg clearance while turning, accelerating, and braking. Additionally, we prioritized driver visibility and head support with an adjustable headrest design. Added driver comfort comes from the two-position steering gearbox and the eight-position pedal assembly. The reclined driver position also improved our longitudinal weight balance while lowering the CG height. To accommodate the reclined position, the nose of the car had to be lengthened, placing mass further from the center of the wheelbase. The reclined position lowers the driver's torso, further reducing the overall CG height. Since our car is rear wheel drive, most of the heavy components are in the rear. The central placement of the accumulator further improves this weight balance. We designed the chassis such that the accumulator was at the lowest point, further lowering CG height, while also matching the contours of our diffuser to generate downforce.

To achieve shorter load paths, we finalized the frame design after the suspension points had been set. This allowed us to place frame nodes as near suspension pickup points as possible, allowing only pure tensile and compressive forces to be exerted on the chassis. We also took care to locate nodes near drivetrain components such as the differential and motor, to reduce the bending loads on frame members. We intentionally designed the drivetrain supporting members to use tubing with a thicker wall than required by the rules, which was validated by FEA analysis and mitigated the concern of a tube failure due to bending. Through further FEA analysis, we were able to validate an increase in torsional rigidity of 11% compared to our previous car, now with a stiffness of 1429 Nm/deg. A rigid frame allows us to more effectively tune our suspension without frame flex confounding our changes.

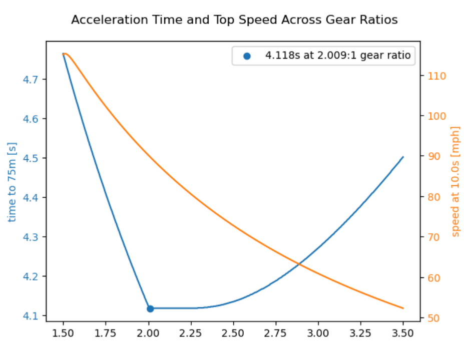
Before the development of the chassis, we finalized the accumulator footprint and selected components such as the motor, inverter, differential, cooling pump, radiator, and steering rack. This allowed us to tightly package all of the aforementioned components. An advantage of this approach is that we were able to robustly isolate the driver from all the high voltage electrical systems without sacrificing performance. Despite the driver being only inches away from the accumulator, they are always protected by the accumulator container, firewall, and seat. Since tight packaging can often come at the expense of serviceability, we generated motion analyses of components being installed and removed to verify clearances. The tight packaging of components allowed us to make the frame significantly lighter and more compact, than our previous chassis.

To validate driver safety beyond the requirements, we ran an FEA analysis on a chassis front-end impact. The analysis uses a 20g load spread evenly across the front bulkhead. We assumed an absolute worst-case maximum weight of 750 lbs, which results in a total force of 67kN, or 16.75kN on each corner of the front bulkhead. The 4 rear pickup point nodes were set as fixed. The minimum factor of safety is 1.134, which means that the driver will be protected.

The controls in the cockpit are easy to use as our steering system has been deliberately designed with a low steering effort. This allows students to spend their energy on driving well instead of straining to steer. The steering wheel also has an integrated screen that shows our dashboard, displaying relevant telemetry such as per-lap energy usage, and has two dials to configure different parameters of the car such as acceleration and braking profiles. All of our critical performance and usability parameters can be easily viewed and adjusted while on track.

Powertrain Architecture

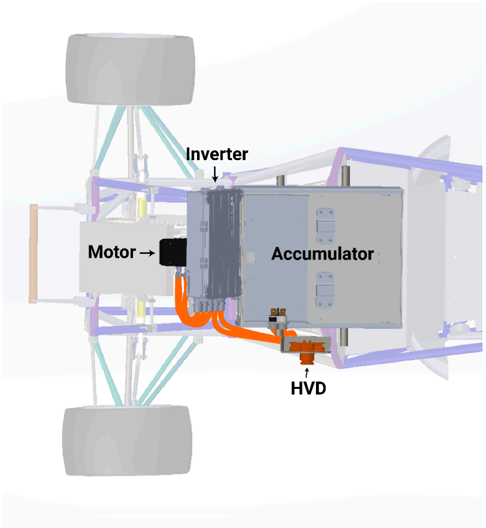
As with all systems of our car, our powertrain architecture was designed to maximize competition performance while staying within the constraints of our cost targets and rules compliance. This year, our primary goal was to be limited by the traction of our tires instead of the torque available from our motor, allowing us to design useful traction control systems and operate as close as possible to our car's performance ceiling. Looking at track data, we also found that last year, we were hitting our (quite low) top speed, so we wanted to increase that as well. To meet these goals, we estimated that we needed to be able to approximately double the peak power from last year's car from 40kW to 80kW.



To learn what we needed to do to meet these goals, we built a drivetrain acceleration simulation using a first-order model of an interior permanent magnet motor and a Pacejka tire model based on data from the FSAE Tire Test Consortium. Coming into the year, we already had an Emrax 228 HV motor. Although we are more in the intended voltage range of the 228 MV, we found that the increased torque constant of the HV variant makes it better for our application. Using the simulation, we determined that a peak output current to the motor between 200 and 250 amps would be optimal for delivering high torque while retaining traction.

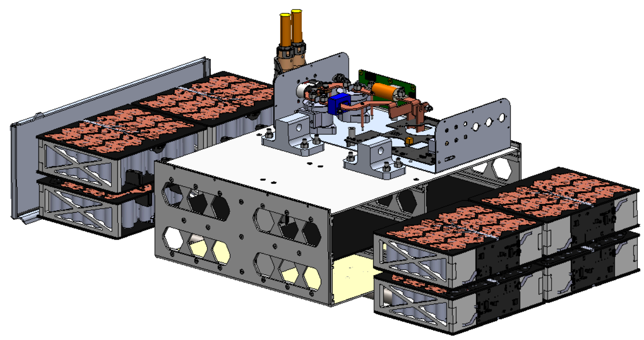
The above graph shows that at 250A (limited to 80kW of input power), the range of optimal gear ratios is approximately 1:2 to 1:2.3 for the acceleration event. We decided to choose a gear ratio of 14:30, or 1:2.14, as it is in the middle of this optimal range and should provide the most flexibility.

With the parameters of 250A motor output current and 80kW peak power output set, we began looking for an inverter that would meet these criteria. The two optimal choices appeared to be the Cascadia Motion CM200DZ and the Sevcon Gen5 Size9. The Cascadia option appeared to be the better choice due to packaging and slightly higher performance, but the price and lead time were extremely



high. The choice was more or less made for us when we were approached by a sponsor who had a spare Sevcon inverter that they were willing to donate to the team. This set the upper bound on accumulator voltage to ~400V, which ideally positioned us to design a 5p96s pack architecture that almost perfectly meets the 5400Wh Formula Hybrid capacity limit. Fusing the pack at 150A allows us to source peak power from the accumulator for up to 10 seconds while being able to pull a very respectable 60 kW continuously. To keep our wires as light as possible and minimize minimum bend radius, we chose Champlain EXRAD XLE 35mm^2 cable and an Amphenol Powerlok connector. This connector is rated for 300A and is easy to crimp, assemble, and inspect, making it extremely reliable.

Energy Storage



When designing our latest fully custom accumulator, we had three sets of goals in mind. First, and most importantly, reliability and serviceability. It does not matter how good our car is if we break a spot weld during endurance and have to retire. On the serviceability side, we wanted to be able to fully replace a segment in five minutes during on-track testing. These targets were developed from experience with our last car, which regularly broke spot welds and was not serviceable outside of our shop. Our second set of goals were performance oriented. We wanted to get as close as possible to the FH capacity limit of 5400 Wh while staying under a total accumulator weight of 130 lbs. Our third set of goals were manufacturing and assembly focused. We wanted to make the accumulator realistic to manufacture and allow all of the assembly work to be done without high voltage present, maximizing safety and efficiency.

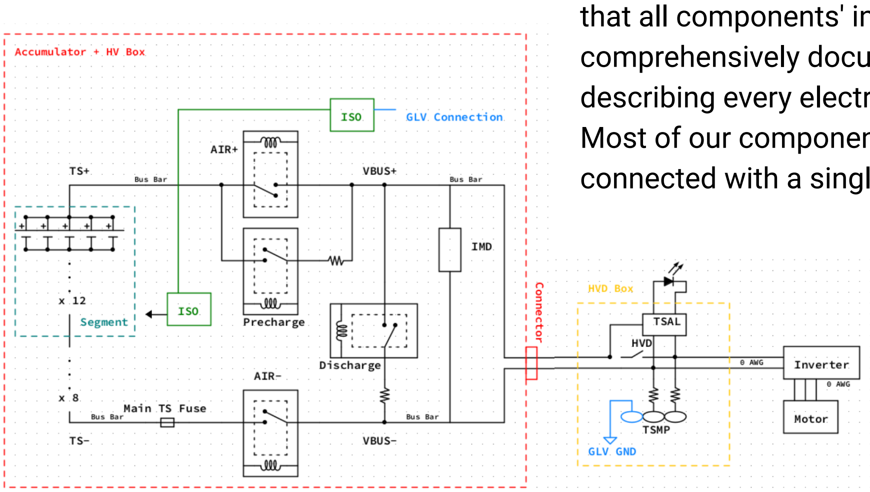
To meet our serviceability goal, we designed the accumulator to contain eight segments that slide into the aluminum accumulator container on rails made of UHMWPE, which we selected for its low friction, high shock absorbance, and relative ease of machining. Each segment is made up of 60 Molicel INR21700-P42A lithium ion cells. When slid in, each one plugs into backplane connectors for our main TS path as well as our low voltage communication bus. The slide-in segments also act as foolproof SMDs, making safety the default option when working on the accumulator. In fact, the entire accumulator is constructed with zero volts present, and high voltage safety procedures are only necessary when adding and removing segments.

Historically, our accumulator reliability issues have stemmed from faulty spot welds and finicky COTS AMS hardware. Through testing, we determined that the primary reason for failed spot welds was mechanical stresses between the spot weld and cells. We epoxied the cells into the structural G10 PCB that holds them as well as the copper plates that they are spot welded to. The cells cannot move relative to the copper plates at all, eliminating repeated bending stresses that persistently plagued previous packs. To address our AMS issues, we designed a fully custom distributed AMS using LTC6811 BMS chips and STM32 microcontrollers with robust error checking and handling. This also significantly reduced accumulator cost, as COTS BMS solutions tend to be very expensive. To test our reliability metrics, we built an automated cycling rig that repeatedly charges and discharges our pack, optionally while under heavy vibration, to test mechanical and thermal cycle loads. The testing gives us detailed data on how every single cell group in our accumulator performs. Our SOC estimation model integrates this data in combination with conventional Coulomb counting estimation. One key oft-missed SOC detail is that pack capacity is strictly limited by the lowest-performing cell group. We are able to include this in our SOC estimation because of the data we collect on our test bench.

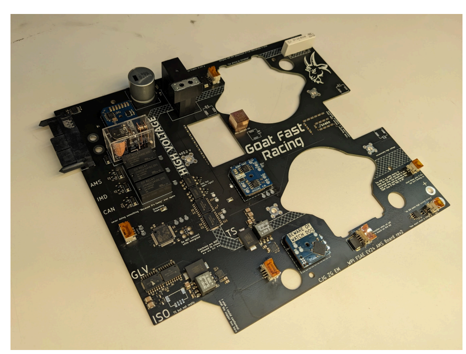
Electrical and Controls

Reliability is the primary design goal of every subsystem on our vehicle. Because of the heavy emphasis on the single endurance event in Formula Hybrid, failure of the electrical system is unacceptable. We also made sure to design systems to improve our on-track performance; being lightweight, maintainable, and collecting useful real-time telemetry data.

To achieve these goals, we follow two key guidelines. First, we develop in-house electronics when COTS parts are less reliable, repairable, or packageable. We build most of our electronics ourselves – the only COTS PCBs inside of our car are in our inverter and our IMD. Second, we guarantee that all components' interactions are simple and comprehensively documented. Our specification sheet describing every electrical interface point is a single page. Most of our components throughout the car are connected with a single wire run of bundled cable containing our shutdown loop, power, and GLV CAN bus. In order to achieve such tight packaging, we developed stamp-sized “sensor boards" that sit in line with this wire and interface with sensors. This allows the sensor boards to be placed in any location. These sensor boards, and all other data-transmitting components in the car, transmit telemetry in a standardized format on one of two “channels” - a 200Hz high latency channel that transmits four 16-bit values at 50Hz or a 200Hz low latency channel that transmits at collection frequency. Our CAN bus use has been rigorously defined so we can guarantee 20ms latency for all packets and 3ms for critical packets.



We utilize a monorepo for all of our boards and code, a shared base from which all team members work. We share schematics between boards for tested designs, reducing design and bringup time substantially. The vast majority of our code is processor-agnostic and shared between all boards. This codebase integrates directly into our dashboard (shown both remotely, and on our steering wheel) giving us a single source of truth for how our communication protocol functions.



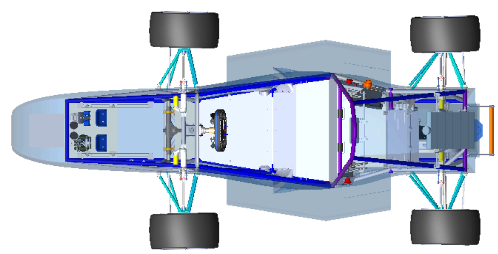
Inside our accumulator and HV box, our custom segment AMS boards communicate over a CAN bus electrically isolated from both TS and GLV. This CAN bus is designed with the same communication schema as our GLV bus and has the same latency and bandwidth guarantees. Our HV box consists of a single "motherboard" PCB connecting all individual components, decreasing the chance of incorrect assembly and damage, a design that allows for rapid failure diagnosis.

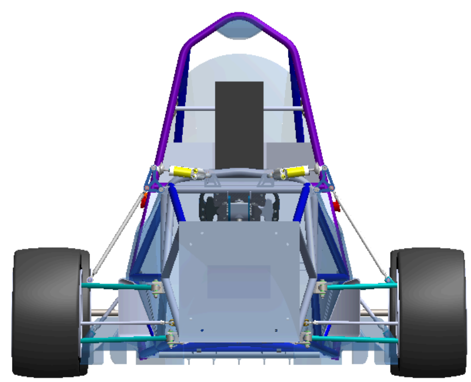
Keeping with our in-house philosophy, we built a 12S lithium-ion GLV battery which is electrically identical to our HV segments, letting us reuse board designs and code. A bidirectional DC/DC converter outputs 24V, supplying the entire car with a clean and consistent bus voltage.

When building so many boards, component selection is critical. We assemble all boards in-house so that we can keep parts on hand for repair and modification purposes. You can read more about this in the sustainability section, but we track every single individual component used on the car. We have several components that are used on more than a dozen unique boards each, and we can guarantee that we have enough stock to build another board before we order, or fix a broken board at the track.

Aerodynamics

The aerodynamic goal of EV24 was to reintroduce aerodynamic design and composite manufacturing to the team. Our requirements were to maximize downforce while maintaining low overall drag, so we chose not to build a front or rear wing. Our scope for this year included the car's underbody, diffuser, nose cone, and side panels.





To improve the effectiveness of our aerodynamics, the leading edge of our nose cone is raised to encourage air to travel under the vehicle, improving the performance of the car's underbody and diffuser. The design of the undertray and diffuser was heavily based on the Venturi effect. We took advantage of the geometry of the frame to vertically constrict the air followed by a large expansion. We built fins into the undertray that serve the same purpose but horizontally. The angle of the rear diffuser is 15°, as research and simulations indicated that 10° was the minimum to start observing benefits and 20° was ideal but also the most sensitive to disturbances. We also designed two "side diffusers" to generate more downforce given the limited amount of volume underneath the car. They follow the same principles and have the same angle as the main floor but only constrict the volume in the vertical direction. Lastly, we also designed carbon panels that encapsulate the rear of the car to encourage the flow of cooling air through our radiator while maintaining a streamlined design to minimize fluid separation. The side panels also retain the 3D-printed accumulator cooling sidepod intakes. We conducted CFD and thermal analysis on the accumulator to ensure that the ram air from these intakes was sufficient for cooling during long endurance runs.

Due to the rather low speeds and emphasis on efficiency, we think that this design will be very effective during dynamic events, where keeping drag low is much more important than downforce.

Sustainability

As participants in an electric car competition, sustainability is at the core of what we do. Our primary goal is to be sustainable as an organization. As such, we strive to encourage the interests of potential members, facilitate knowledge transfer, and build durable systems. This year, we have hit all of these targets. The core of our team consists of students completing their senior capstone project, but this year junior members of the team conducted seven independent study projects in which younger students committed to doing as much work as our core capstone team in exchange for class credit. We've found that using the independent study framework to transfer knowledge is very effective in encouraging team members to get involved in a substantive way that can be more daunting for people taking a full non-FSAE courseload. Individuals who complete independent study projects consistently join the capstone project in later years.

In addition to sustaining the health of our organization, this year the team focused heavily on environmental sustainability. The most environmentally detrimental thing that we could do is discard usable systems. While system redesigns can be unavoidable, our design philosophy focuses on building components that can be iterated on for two to four years - in doing so, we effectively reduce waste by 50-75%. Our previous car was an active project from 2020-2023, allowing us to triple the lifetime of environmentally unsafe systems, especially batteries. As an electric car team, Li-ion cell disposal is something we are extremely aware of from a sustainability perspective. Using the same pack for three years allowed us to effectively save two full packs of cells from the landfill. In addition to that savings, we work hard to save any component ranging from metal and plastic parts, wire, connectors, carbon fiber bodywork, and more that make up the rest of the car.

Fortunately, WPI has one of the leading research laboratories on Li-ion cell recycling, the WPI Electrochemical Energy Laboratory. As a team, we are actively working with their lab to ensure that our used or destroyed cells make their way into real recycling channels that genuinely recycle the rare metals towards new cells for the future - while also contributing to novel research on Li-ion recycling.

A major sustainability initiative for this year's competition team is our electrical component inventory system built with InvenTree. This system allows us to organize and track our more than 250 individual parts that range from passives to more expensive or rare ICs. The majority of these parts arrive in quantities of 100 or 1000, frequently leading to excess stock. Understanding what is already in our possession allows us to avoid overordering no matter the part. Each part that we put in a design gets an internal part number, and stock is tracked on a per-location and quantity basis. Ordered stock gets put in a uniform bag, put in a location tracked by software, and sorted by number. InvenTree allows us to ensure that we have adequate stock, but the real time savings stem from an easily searchable list of parts. This allows us to reference our database to - for example - avoid purchasing three similar resistors for three different boards. This system also makes impromptu repairs or on-track fixes easier - as we have a much wider selection of components to choose from and a way to effectively sort through them. As such, we can avoid leaning on overnight shipping, a process that hurts our timeline and the planet. This is a system that is going to carry cost and time savings into the future, allowing future teams to maximize sustainability as well.