OVERALL TEAM GOAL

2005 marks the tenth consecutive year Dartmouth Formula Racing (DFR) will compete in the Detroit FSAE Competition. The team has exhibited an impressive record over the years, placing amongst the Top 20 finishers seven out of nine times, including two finishes in the Top 10 overall. DFR now aims to firmly establish itself as one of the powerhouses of the FSAE event and has made its primary goal to achieve a first-ever Top Five overall finish at the 2005 competition.

The team intends to reach the 'Top Five in 2005' by focusing on the dynamic performance of the car. Competitive analysis demonstrates that DFR must gain more points in autocross and endurance to compete with the frontrunners at competition (see page 8). To improve in these areas, the team has developed a greater understanding of vehicle dynamics and studied methods of enhancing cornering performance on the track. With the aggressive redesign of all major vehicle systems and the implementation of a new data acquisition system, this knowledge will allow the team to reach the car's full performance potential and help us outperform the competition in Detroit.

OBJECTIVES AND SPECIFICATIONS

With our sights set on the 'Top Five,' the DFR team adopted three principle design objectives for the 2005 campaign. First, in an effort to improve overall dynamic performance, the team sought to <u>reduce vehicle weight</u> by 40 pounds (lb) to 449 lb while lowering the center of gravity with driver (CG) to 12.5 inches (in). Second, the team aimed to <u>optimize the driver-vehicle controls interface</u> to make the car easier to drive around the track. This included improvements to the mid-range engine power band, brake modulation and control, and revised shift and pedal package systems. Third, to improve performance in autocross and endurance, the team aimed to <u>maximize dynamic vehicle performance through comprehensive suspension analysis and track testing</u>. The team therefore developed a thorough track testing/tuning protocol and designed a custom data acquisition system to study the dynamic behavior of the suspension as well as the brake and engine systems. At the track, the team aims to increase lateral acceleration from 1.21 to 1.45g and complete a 0-75m acceleration run in under 4.2 seconds.

DESIGN METHODOLOGY

The car has been redesigned from the ground up to lower weight and improve drivability with intentions of improving dynamic performance. Almost every part was modeled using Computer Aided Design (CAD), Finite Element Analysis (FEA), and Computational Fluid Dynamics (CFD) software packages to study projected loading scenarios, ensure inter-component compatibility, and model fluid flows where applicable. Experimental tests of the frame, suspension, engine, and brake system components were also conducted using mechanical test machines, an engine dynamometer, our on-board data acquisition system, and/or other lab setups.

FRAME

A redesign of the tubular 4130 steel frame was necessary to achieve the target weight savings and improve packaging of components near the rear axle. Designed and analyzed using Pro/Engineer and SusProg3D software, almost every major dimension of the frame has been reduced in an effort to save weight. Having observed the excellent dynamic performance of smaller cars at FSAE and Formula Student in 2004, the team adopted smaller wheelbase and track widths in an effort to make the car more nimble in tight radius turns. The wheelbase was shortened by 4.0 in to 65.0 in while track widths front and rear were set at 47.0 and 45.0 in, respectively. To maintain stability within the smaller platform, the CG was lowered through revised driver positioning and component packaging. The desired 45/55 weight distribution was maintained by mounting the engine far rearward in the frame and reclining the driver's torso to a 40° angle with the horizontal, a change that also lowered his CG by 1.5 in. The redesign also relocated the pedal package and steering rack to the bottom frame tubes, further lowering the CG and providing more knee room within the shortened wheelbase. Increased triangulation and the smaller wheelbase permitted a narrower frame midsection and greater use of 0.049 in tubing, resulting in a 5.0 lb frame weight loss to 63.5 lb. Preliminary testing of the frame demonstrates a torsional stiffness of 1100 ft-lb/degree, slightly below our 1200 ft-lb/degree target but approximately equal to past DFR cars. The team will conduct track testing March 17-24 to confirm that this stiffness is adequate.

TIRES, WHEELS, AND SUSPENSION

The tire, wheel, and suspension package was completely redeveloped to meet our dynamic performance objectives and excel in autocross and endurance. The redesign began with the creation of Understeer Gradient and Pacejka models corresponding to our frame design and selected tires. R065 Goodyear tires (20x6.5-13) were chosen based on skidpad test results and their Pacejka tire coefficients for lateral force, longitudinal force, and self-aligning torque. When inflated to 11 psi, these tires exhibit excellent sidewall stiffness and lateral grip characteristics that result in predictable cornering behavior and more accurate and effective suspension tuning.

The 2005 team chose one-piece, cast magnesium alloy centerlock wheels to minimize both unsprung and rotating mass. The switch from the two-piece, three-bolt wheels used in 2004 yielded 2.5 pounds in total weight savings as well as allowed smaller, lighter hubs at all four corners. The front wheels mount to a new one-piece hub/spindle component supported by tapered bearings integrated into the front uprights. The steel “Hubindle” was heat treated to a Rockwell C hardness of 35 to reduce stresses in the welds and increase strength. The design saves 1.5 lb relative to the outgoing hub/spindle assembly, simplifies the manufacturing process, and decreases the scrub radius substantially.

The 2005 unequal length, short-long arm suspension has been completely redesigned for the smaller and lighter vehicle, with improved adjustability throughout. The front and rear roll centers were set at 2.07 and 2.29 in, respectively. Both the front and rear suspension incorporate a shim-based camber adjustment system at the wheel, facilitating simple and quick camber changes without affecting toe settings in the range of 0 to -3 degrees. New in 2005 is the Slot-Slug caster adjustment system in the front, allowing easy adjustments from 2 to 8 degrees using two sets of upper control arms and ‘slugs’ on the frame side. As is the case throughout the vehicle, all suspension fasteners are standardized to AN-type bolts and lock nuts to ensure high quality and simplify servicing and reassembly.

All non-adjustable suspension linkages have been manufactured with spherical bearings pressed into chamfered housings. As in 2004, these bearings were chosen to eliminate threads in bending at the Heim joints, minimize friction, and preserve control arm geometry under cornering, brake, and bump loads. The front and rear uprights are fabricated from 4130 sheet steel to maximize stiffness and minimize weight. Both have been redesigned and use thinner gage steel in their construction, permitting a total weight savings of 2.0 lb compared to 2004 with negligible change in deflection under projected corner, brake, and bump loads.

Coupled with track and shock dynamometer testing, Understeer Gradient and Pacejka models were also used in the selection of our springs and dampers. These models provided a means for the team to generate a set of spring and damper specifications that would maximize lateral grip during cornering. Given our selected tires, roll center heights, CG position, and target weight, DFR chose front and rear spring rates of 350 and 400 lb/in, respectively. Fox Vanilla shocks were selected for our application because they exhibited consistent spring and damper rates throughout compression and rebound and satisfied specifications for weight, packaging ease, and cost. To fine tune the roll stiffness of the car, DFR designed torsion-bar type anti-roll bars (ARBs) adjustable in the range of 3000 ft-lb/rad to 5000 ft-lb/rad in the front and 1000 ft-lb/rad to 3000 ft-lb/rad in the rear. These ranges were selected based on weight transfer calculations employed in our Understeer Gradient model.

POWERTRAIN

Owing to its power, reliability, and the compact dimensions afforded by its ‘stacked’ transmission, DFR selected the 599cc Yamaha YZF-R6 engine for the 2005 car. Virtual4Stroke

(V4S) software analyses and engine dynamometer testing demonstrated that the 20mm air restrictor chokes the stock R6 engine at 12,500 rpm, 500 rpm shy of its normal power peak. The team thus aimed to tune the engine for greater flexibility and usable power on the autocross and endurance tracks by maximizing torque through the engine midrange (6,000–10,000 rpm).

DFR identified the camshafts as the most effective, efficient, and reliable method of reshaping the engine‘s power curve. The V4S package was used to redesign cam profiles in consideration of the air intake restrictor and our desired power band characteristics, decreasing intake and exhaust valve duration by 58 and 11 degrees to minimize overlap and reach peak power before the choking point. This design results in a desirable ‘plateau-shape’ torque curve that provides more power throughout the midrange.

FLUENT fluid modeling software, V4S, and engine dynamometer testing were used to design the intake specifically for the new camshafts, again aiming to maximize midrange power. Starting from the successful past use of a 34mm butterfly throttle body, short diffuser, and static box plenum, the modular intake assembly was designed in Pro/ENGINEER and then constructed of ABS plastic using Rapid Prototyping (RP). The parts were then vacuum cast using silicon-based molds and polycarbonate thermoset injection plastics. The result is an intake system that is not only strong and lightweight—the polycarbonate plastic is 40% as dense as aluminum but has nearly equal the yield strength—but also allows different configurations to be easily and iteratively tested on the dynamometer.

A new Performance Electronics Engine Control Unit (ECU) is employed to manage the sequential fuel injection and capacitive discharge ignition through stock Yamaha plug-mounted coils. Fuel maps optimized for the new camshafts were developed through extensive manual and automated testing on the DFR engine dynamometer. Preliminary testing of the ECU with the new camshafts, air intake, and exhaust demonstrates a distinct overall improvement over low and midrange rpm as well as peak power: nearly 40 ft-lb torque is available from 6,000-10,000 rpm, with power peaking at 75 bhp at 10,500 rpm (see page 8). These increases in midrange power and torque will help us exit faster out of every corner, giving the car a distinct advantage on the autocross and endurance tracks.

DRIVETRAIN AND BRAKING

The drivetrain and braking systems were completely redesigned in accordance with our objectives of enhancing driver control, improving dynamic performance, and reducing weight. Complementing the shift in the engine power band with the new camshafts, intake, and exhaust, the final drive ratio was lowered slightly to 4.10:1 to make use of midrange power during the autocross and endurance events. Also, with the implementation of a temporary ignition cut switch for “no lift” shifting, the modified power band and selected final drive ratio allows the car to be launched from a standstill in second gear. This eliminates the need for drivers to shift through neutral during the acceleration run and helps drivers make the most of available power while on the track.

The differential drivetrain assembly is constructed around a Torsen Type-1 limited-slip unit with a torque bias ratio (TBR) of 4.0:1 under drive and 2.8:1 under braking. Lateral weight transfer that occurs under 1.45g cornering prompted DFR to choose this differential over others that weighed marginally less but exhibited lower TBRs. An iterative design and stress/lifecycle analysis process was applied to all components surrounding the Torsen in an effort to reduce rotating weight while maintaining necessary strength. The differential encasement, cradles, stub shafts, bearings, endcaps, and tripod housings have all been thoroughly revised and studied through FEA, resulting in a remarkable 13.0 pounds in drivetrain weight savings relative to 2004. A new sliding-cradle chain tensioning system was also designed to both save weight and maintain a constant chainline attitude throughout the range of adjustment, maintaining clearances within the tight packaging near the rear axle.

The 2005 car exhibits dual rear brakes in accordance with our objective of maximizing dynamic performance. This choice ensures balanced braking torque when trail braking, reducing brake-induced understeer at turn-in. This will increase cornering consistency and predictability on the track, aiding in the process of suspension tuning and helping us excel in the autocross and endurance events. Static and thermal brake models were created and verified at the track in order to determine the optimal combination of brake system parameters such as rotor diameter, material, mass, pad sweep, and caliper piston and master cylinder bores. The system was designed to minimize weight, permit lockup at the brake test, and remain below maximum recommended brake pad temperatures during a 'worst case' braking cycle at the endurance event. The front brakes are Wilwood Billet Dynalite calipers with PolyMatrix Q pads and 10 inch aluminum-silicon-carbide metal matrix rotors, a package which yields 3.6 pounds of weight savings relative to the 2004 front brake package. The rear brakes are Wilwood PS-1 calipers with 7 inch steel rotors custom designed for our performance and packaging specifications. They are mounted inboard to maximize the rate of convective cooling and avoid adding to unsprung weight.

ERGONOMICS

Consistent with our objective of optimizing the driver-vehicle controls interface, the 2005 driver cockpit has been completely redesigned to enable quicker shifting, improve pedal package ergonomics, and simplify instrumentation. The new frame positions the driver in a more reclined seating arrangement with his legs slightly elevated over the low-mounted steering rack, permitting a more form-fitting seat structure with increased thigh and hip support. A pneumatic shift system allows the driver to change gears up or down at the push of one of two buttons mounted on the steering wheel. The simplicity and speed of the system's operation more than compensates for its marginal weight gain over a mechanical linkage. Controlled by three-way electric solenoid valves, the system uses a lightweight air cylinder with enough capacity to shift through the equivalent of four endurance events. The low-effort hydraulic clutch, used primarily for startup, has been located on the steering wheel to provide more room near the pedal package for left foot braking. Up front, there are now two pedals (throttle and brake) that pivot about their base to follow the natural arc traced by the driver's foot. The entire package has 9 inches of adjustability by way of quick-release pip pins, accommodating drivers from 5'3" to 6'5" in less than 30 seconds. Lastly, instrumentation has moved from the steering wheel to a helmet-mounted Heads Up Display (HUD), simultaneously making this system lighter and more legible than in years past.

DATA ACQUISITION

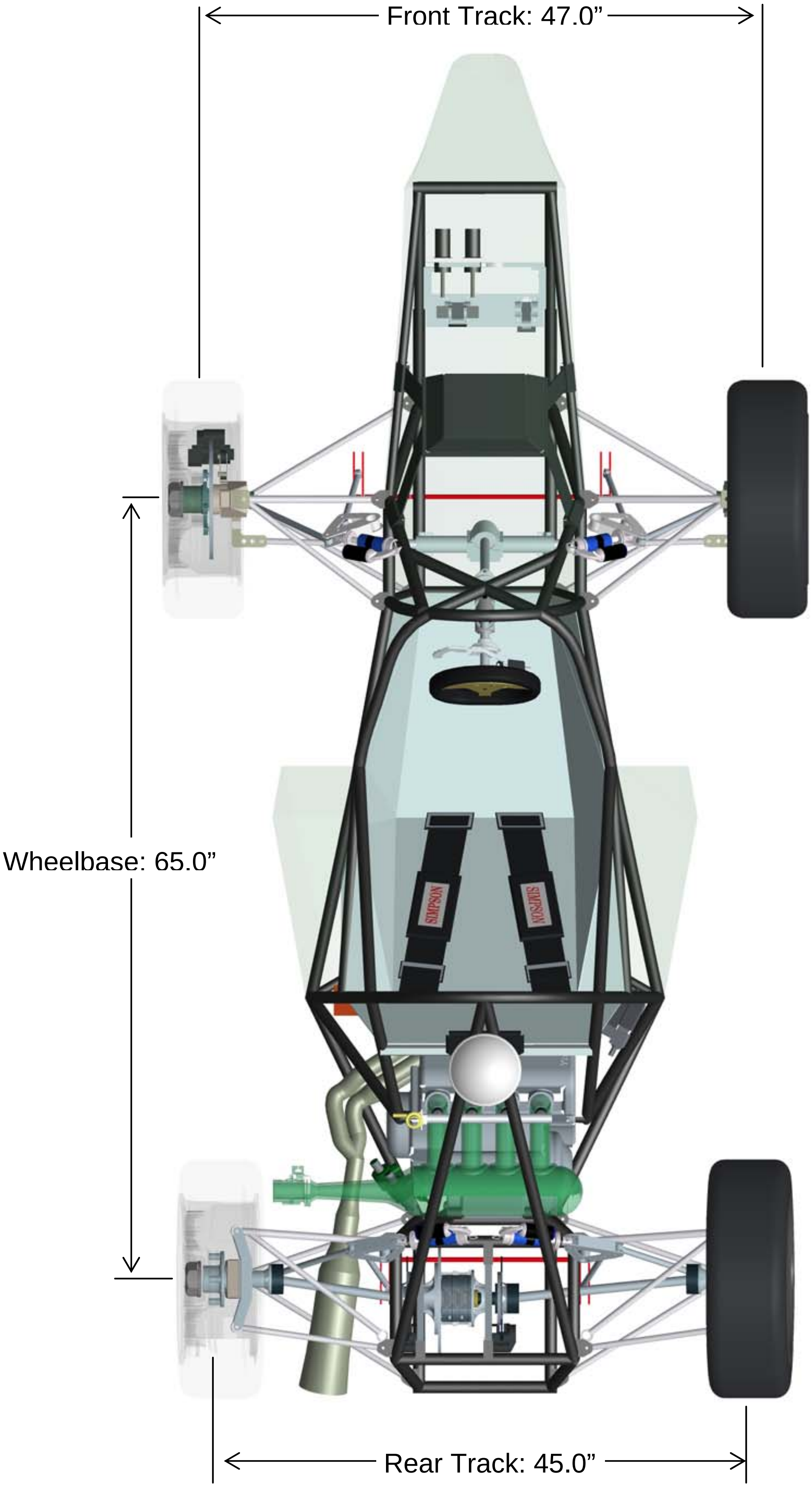
Owing to our objective of improving dynamic performance through comprehensive track testing, DFR decided to devise a custom data acquisition system to monitor, test, and analyze the dynamic performance of most of the vehicle systems discussed in this report. The system was designed in parallel with the main wiring harness in an effort to create a standardized, lightweight electronics platform that will serve as a blueprint for future DFR vehicles.

The data acquisition system is built around a powerful microcomputer, a differential GPS unit, a network of sensors, and a wireless link. During testing, LabView data panels provide real-time, track-map readouts for 20 sensors monitoring the suspension, engine, and brake systems. As the car proceeds around a test course, the team has the ability to monitor and analyze the behavior of a wide variety of systems and download the data from a memory card at the completion of the run. Accelerometers and tire temperature gages along with suspension travel, ARB loading, and wheel speed sensors will be used in conjunction with our detailed tuning protocol to fine tune the suspension for optimal cornering performance. DFR looks forward to demonstrating the data acquisition system and sharing our test results at competition.

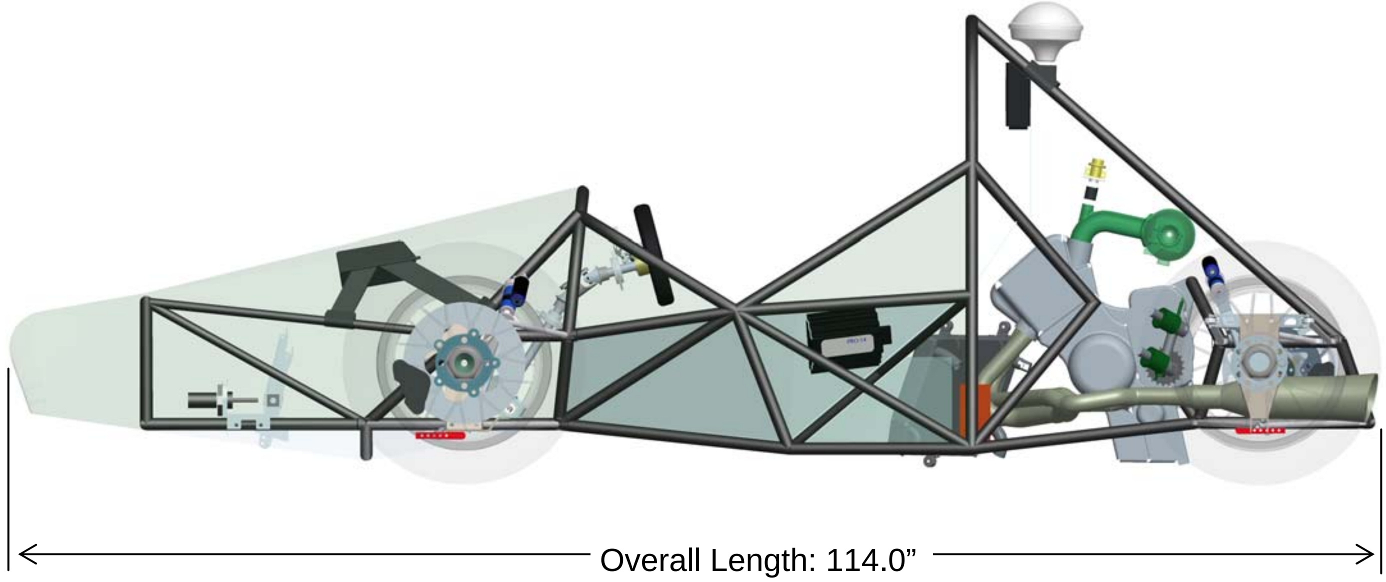
CONCLUSION

2005 has been and will continue to be a year of unprecedented accomplishments for DFR. Our new design is more innovative and sophisticated than any of our previous cars, and it reflects a strong, unified effort to meet our three principle design objectives. With a car that is lighter, easier to drive, and better tuned than ever before, our sights are now set on reaching the Top Five in Detroit.

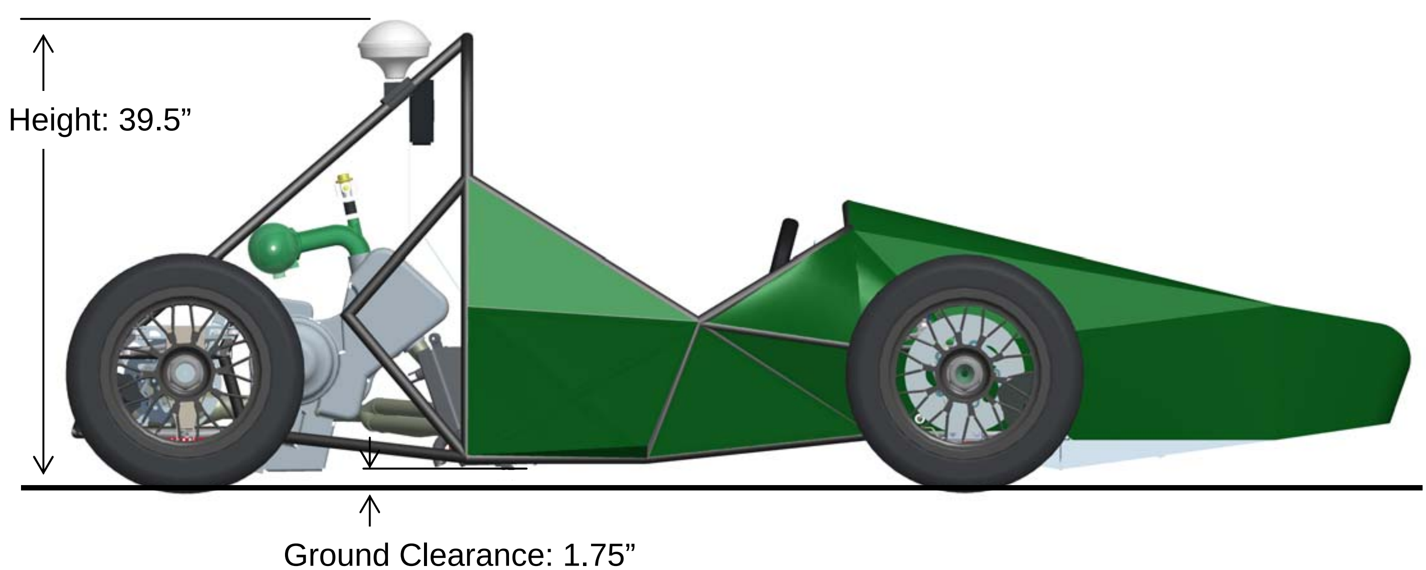
TOP VIEW


Front Track: 47.0”
Wheelbase: 65.0”
SIMPSON
SIMPSON
Rear Track: 45.0”

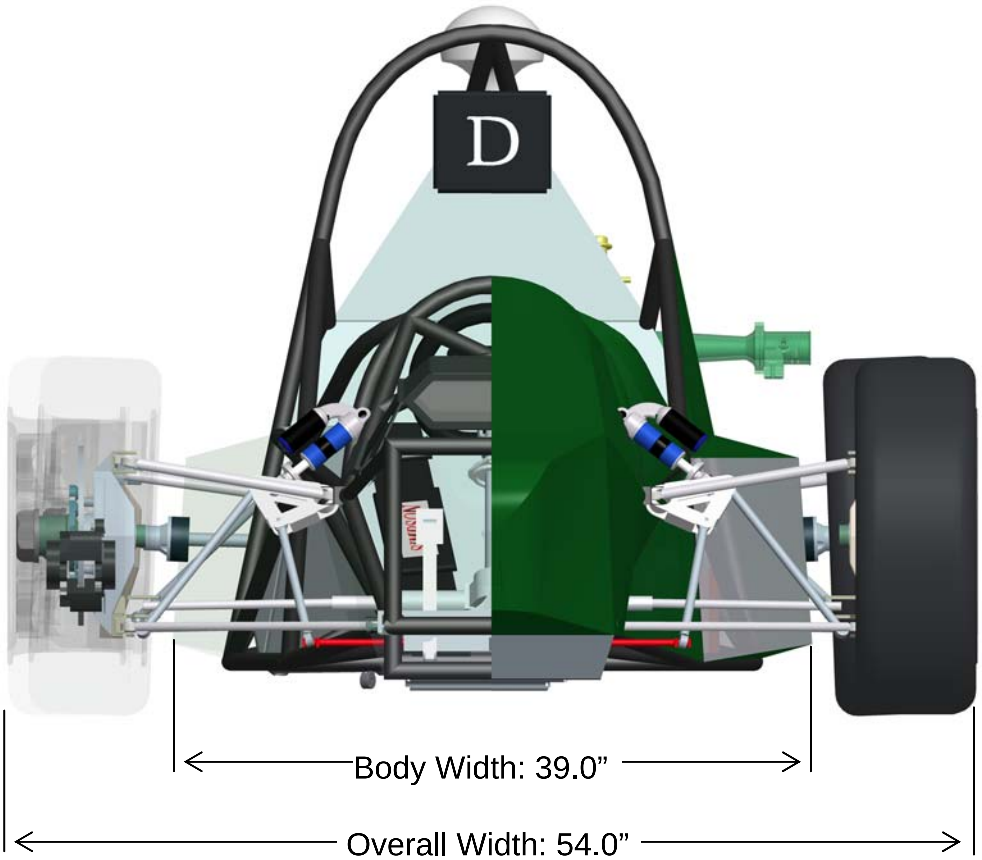
LEFT SIDE VIEW



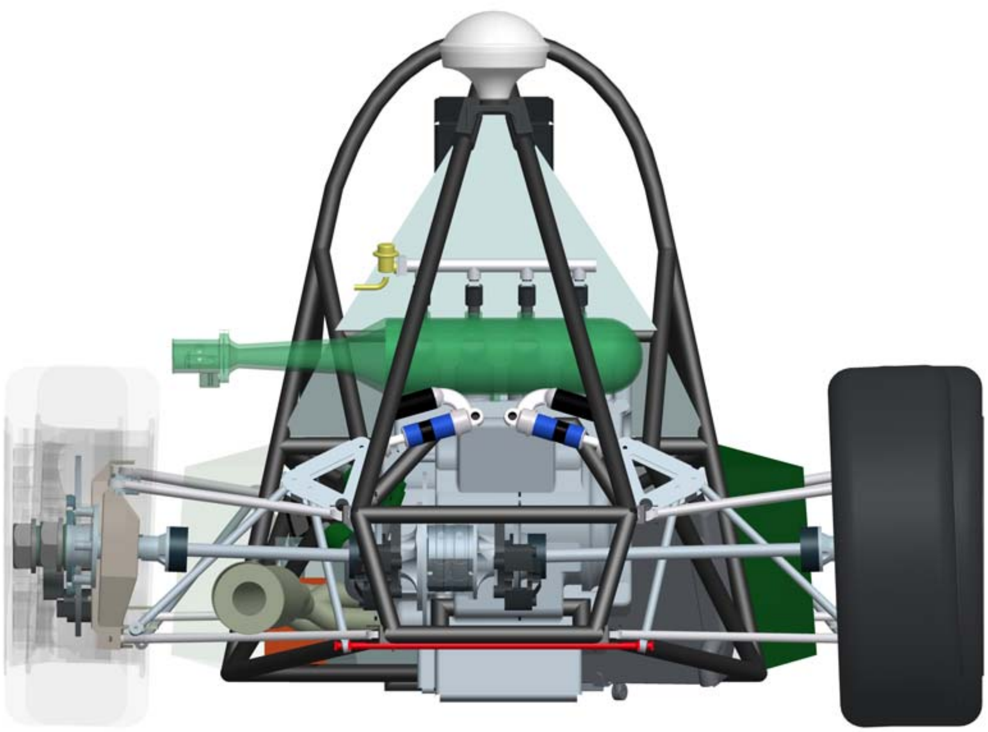
RIGHT SIDE VIEW



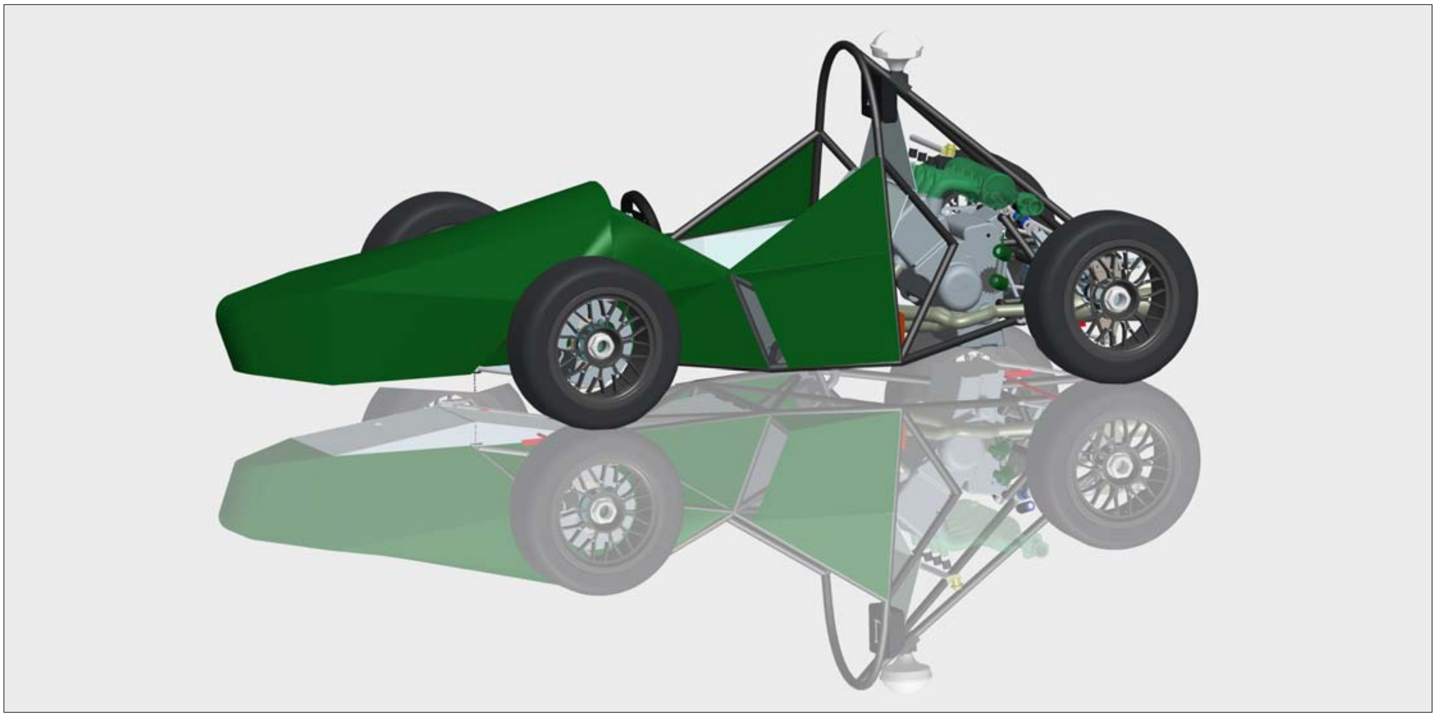
FRONT VIEW



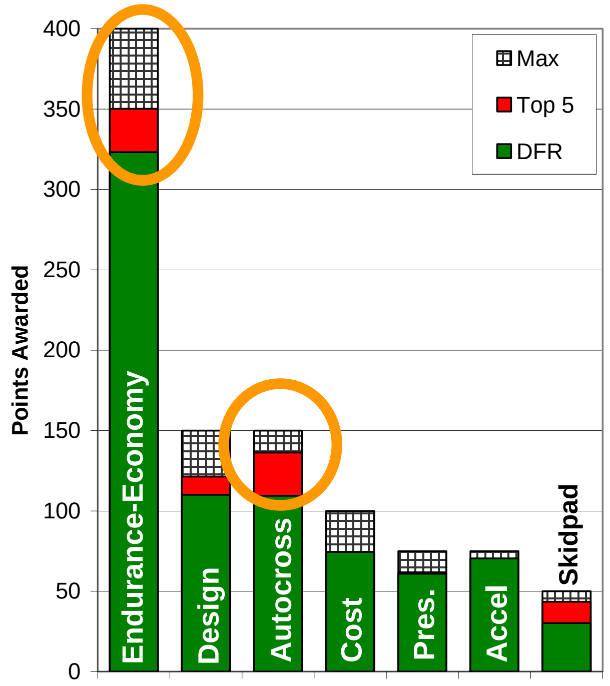
REAR VIEW



ISOMETRIC RENDERING

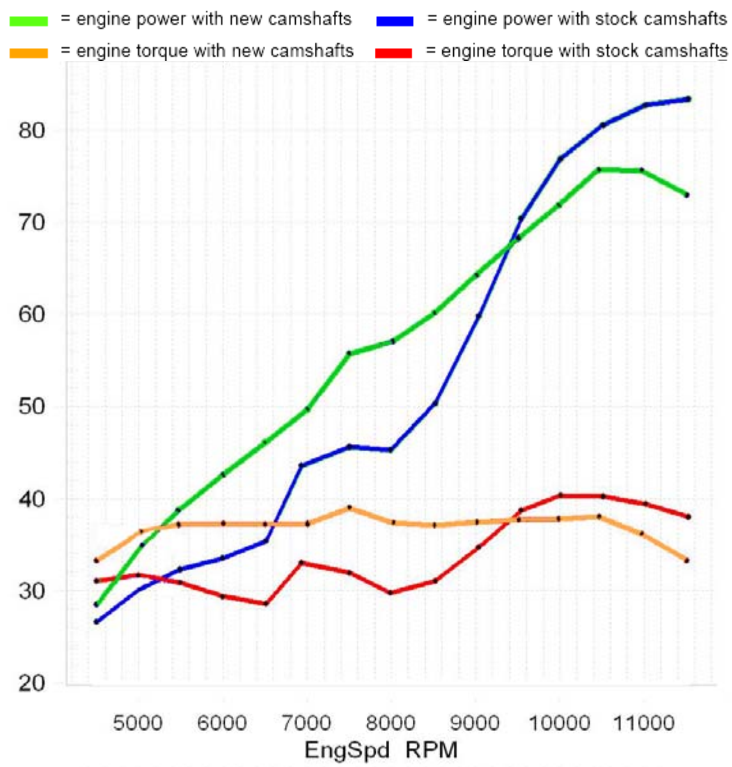


2004 FSAE POINTS AWARDED BY EVENT



Competitive analysis during late summer 2004 highlighted a need for improved performance in endurance and autocross. Similar trends were discovered when reviewing 2001, 2002, and 2003 results. The 2005 team therefore decided to focus on dynamic vehicle performance and driver training specifically for these events.

ENGINE DYNAMOMETER TEST OF DFR CAMS



February 5, 2005 engine dynamometer test demonstrates a significant improvement in midrange power and torque with DFR-designed camshafts. Recent revisions to the intake will increase top-end power.