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Design, Analysis, and Optimization of a High-Performance Powertrain System for a Formula SAE Racecar

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Abstract

The primary challenge in Formula SAE vehicle design is extracting maximum performance from an engine restricted by a mandatory 20 mm intake orifice. This paper details the complete engineering process behind the powertrain system developed for our FSAE combustion vehicle, utilizing a water-cooled 373.2 cc KTM engine. To mitigate the severe choking effect at higher RPMs, we developed a highly optimized intake manifold. This system incorporates a convergent-divergent nozzle to maximize mass flow, a 2.67 L Bezier-curve plenum to stabilize pressure pulses, and a tuned runner to leverage Helmholtz resonance for denser air charges. To efficiently transfer this power to the ground, we implemented a direct-drive spool axle paired with a topology-optimized sprocket, significantly reducing rotational inertia and unsprung mass. Furthermore, we designed a tuned venturi-type exhaust system for effective scavenging and a large-core liquid cooling circuit to manage the severe thermal loads inherent in low-speed autocross racing. The integration of these subsystems resulted in a highly responsive, reliable, and tractable powertrain package tailored specifically for track dynamics.

Keywords: Formula SAE, Powertrain, CFD, Intake Manifold, Drivetrain, Cooling System, Topology Optimization.

1 Introduction

In the highly competitive environment of Formula SAE (FSAE), the powertrain is usually what dictates the overall dynamic limits of the vehicle. The main engineering problem we face isn't just tuning an engine for peak power; it's getting it to perform under the strict regulatory limit that forces all incoming air through a single 20 mm circular restrictor. This constraint heavily chokes the engine at higher RPMs, forcing us to shift our focus away from chasing top-end horsepower and instead prioritize the area under the torque curve and transient throttle response.

For this project, we selected a water-cooled, 373.2 cc single-cylinder engine that natively puts out about 44 horsepower at 10,000 RPM and 36 Nm of torque at 8,000 RPM. However, once you bolt on the 20 mm restrictor, those operational limits change drastically, effectively capping the engine's breathing capacity around 7,500 RPM. To counter this and claw back some volumetric efficiency, we had to rethink the entire powertrain architecture—spanning the intake geometry, the drivetrain ratio, the exhaust scavenging, and the thermal management system.

This paper breaks down the design iterations and validation of these core subsystems. Because we are building for a lightweight tubular spaceframe race car, our designs constantly balance maximum performance with absolute weight reduction and cyclic reliability.

2 Intake System Design

The intake system's job is straightforward but difficult: feed the engine as much air as possible without breaking the restrictor rule. We broke this down into three main areas: the restrictor profile, the plenum volume, and the runner length.

2.1 Convergent-Divergent Restrictor

To maximize mass flow and minimize pressure drops, we bypassed the standard orifice plate and went with a Convergent-Divergent (CD) nozzle. Orifice plates are notorious for boundary layer separation and terrible discharge coefficients ($C_d \approx 0.60$). A well-designed CD nozzle, on the other hand, allows the air to expand gradually, helping us recover pressure and pushing the discharge coefficient up near 0.975.

Through ANSYS Fluent simulations, we tested various angles to keep the flow attached. We found our sweet spot with a 35° converging angle and a very shallow 2° diverging angle. This specific geometry gave us the lowest pressure loss (7,619 Pa) while preventing boundary layer separation.

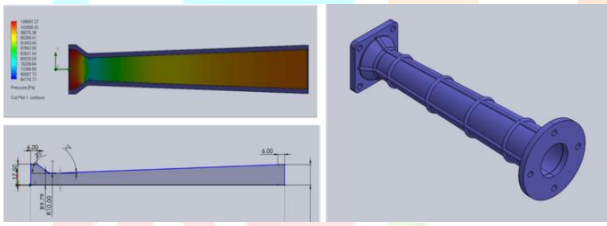


Figure 1: CFD pressure contours of the optimized Convergent-Divergent restrictor.

2.2 Plenum Volume Analysis

The plenum acts like a buffer. Because a single-cylinder engine pulls air in violent pulses, the plenum smooths out that demand so the restrictor sees a more constant flow. A bigger plenum usually means better volumetric efficiency, but go too big and you ruin the throttle response (throttle lag), making the car terrible to drive out of tight corners.

We built a 1D model in Ricardo WAVE and ran sweeps from 1.0 L to 4.0 L. The data showed that horsepower gains really started flattening out after 2.5 L. Factoring in packaging space and the need for sharp throttle response, we settled on a 2.67 L volume.

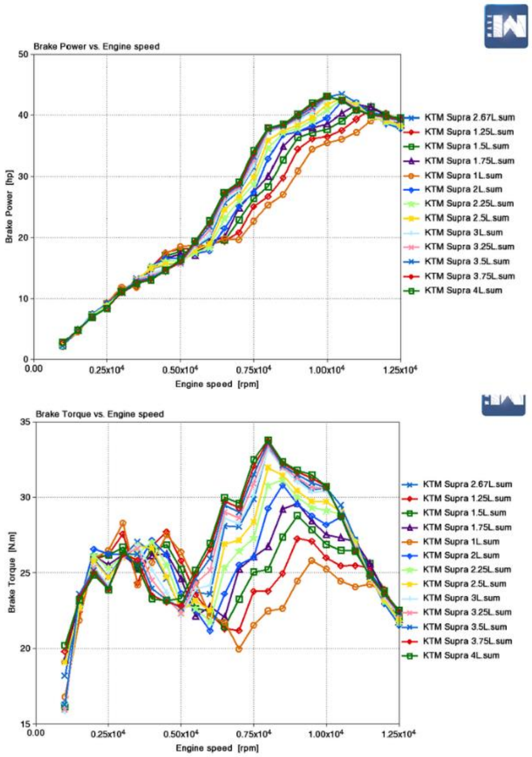


Figure 2: Brake Power and Torque vs. Engine Speed for varying plenum volumes.

To further smooth out the airflow, the plenum itself was shaped using Bezier curves and finished with an elliptical bellmouth pointing into the runner.

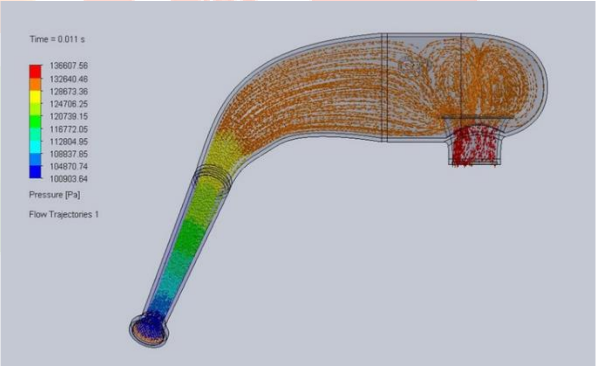


Figure 3: Flow trajectory simulation through the Bezier-curve plenum.

2.3 Runner Length Tuning

Runner length dictates when the engine gets a boost from Helmholtz resonance (the ”Ram Effect”). By timing the pressure wave that bounces off the closed intake valve so it returns exactly when the valve opens again, we can force a denser charge of air into the cylinder.

Targeting an 8,000 RPM operating band, we used Induction Wave Theory to calculate the ideal length. Factoring in our camshaft profile (effective cam duration of 226°), the math pointed us to a length of roughly 10.075 inches (256 mm).

3 Drivetrain Engineering

For the drivetrain, our main goal was minimizing power loss from the output shaft to the tires. A chain-drive system with a solid spool was chosen over a heavy differential to keep things light and simple.

3.1 Topology-Optimized Sprocket

We used MATLAB acceleration models to hunt down the perfect final drive ratio for the 75-meter sprint event. A ratio of 3:1 (15-tooth pinion, 45-tooth sprocket) gave us the best theoretical time of 5.6 seconds without spinning the tires excessively.

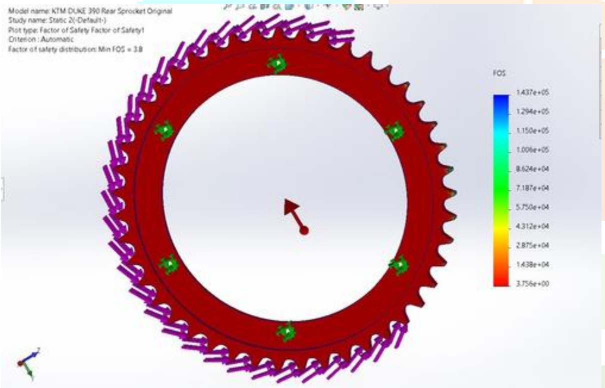


Figure 4: Static stress analysis and topology optimization of the 45-tooth sprocket.

Knowing the sprocket would see up to 742 Nm of torque, we ran topology optimization to strip out material where it wasn’t needed. Laser-cut from 5 mm AISI 304 Stainless Steel, the final piece weighs just 1.2 kg but maintains a factor of safety of 1.2.

3.2 Solid Spool and Half Shafts

A solid spool axle forces equal torque to both rear wheels and entirely removes the heavy differential housing. Machined from Al6063-T6 aluminum, our spool directly mounts the sprocket and a single brake rotor, pulling that rotational mass inboard to improve vehicle handling. The spool mounts were fabricated as box sections from laser-cut stainless steel. FEA showed a safety factor of 2.4 under combined chain and cornering loads.

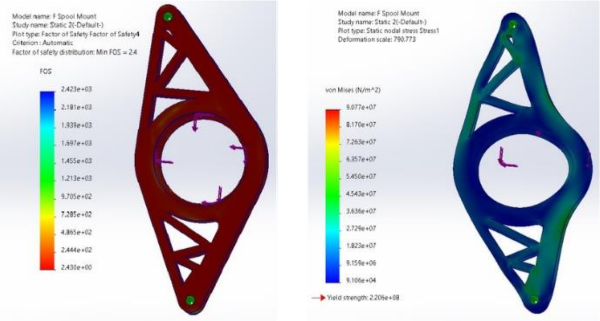


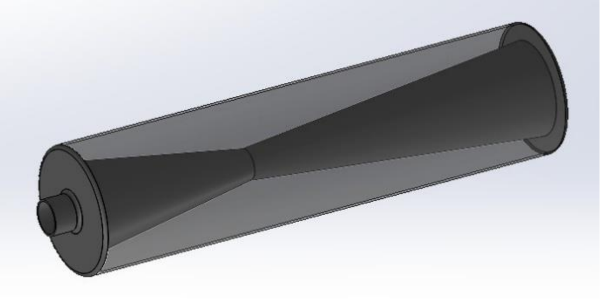
Figure 5: Stress distribution on the box-section spool mounts.

4 Exhaust System and Scavenging

The exhaust had to accomplish two things: pull spent gases out of the cylinder effectively and keep the noise under the strict 110 dBA FSAE limit.

Because single-cylinder engines have aggressive exhaust pulsations, we tuned the header length to use the negative pressure wave to help scavenge the cylinder during valve overlap. We designed a custom venturi-type muffler that steps down from 38 mm to a 22 mm throat, before expanding out to 26 mm. This forced pressure drop kills acoustic energy without choking the engine with backpressure (keeping it in the safe 7-12 kPa range).

Figure 6: CAD of venturi-type muffler.



5 Thermal Management

Stock motorcycle radiators rely on the bike moving fast to push air through the fins. In a Formula Student car, you spend a lot of time waiting in lines or navigating tight, slow autocross tracks, which means airflow is terrible and the engine heats up fast.

To handle the 11 kW of heat rejected by the engine, we ditched the stock setup for a single, large-core radiator. Based on our Log Mean Temperature Difference (LMTD) calculations, we sized the radiator to 310 × 230 × 12 mm. Paired with a high-flow electric water pump pushing 40 L/min and a custom swirl pot located at the highest point of the system to bleed out air, the setup keeps the engine safely at its optimum operating temperature.

6 Conclusion

Getting a commercial motorcycle engine to perform in a restricted motorsport environment takes a lot of specialized engineering. By implementing a Convergent-Divergent restrictor and a precisely tuned plenum, we successfully bypassed much of the regulatory choking effect. Combining this with a lightweight, topology-optimized drivetrain and a thermal management system built for low-speed airflow ensures the vehicle is not just fast on paper, but reliable and highly responsive on the track.

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