



Model Wind Tunnel Project

Preliminary Design Review

Terps Racing EV — Aerodynamics Subteam
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1. Problem Definition and System Requirements

1.1 Problem Statement

The Terps Racing EV team competes in the Formula SAE Electric competition, where aerodynamic performance is a critical differentiator. The team currently lacks the ability to validate aerodynamic designs through physical testing before committing to manufacturing and only relies on digital models. Computational Fluid Dynamics (CFD) simulations provide theoretical insight, but without physical validation, there is no feedback loop to confirm simulation accuracy or identify real-world flow phenomena that CFD may miss.

This project addresses that gap by designing and building a desktop-scale open-circuit wind tunnel capable of simulating airflow over scale models of SAE vehicle components. The tunnel must produce controlled, repeatable flow conditions suitable for both qualitative flow visualization and quantitative pressure measurements

1.2 Subsystem Context

The wind tunnel serves the Aerodynamics subsystem of Terps Racing EV. Its primary function is to provide physical aerodynamic validation data to complement the CFD workflow. Results from the wind tunnel feed directly into design decisions for the front wing, rear wing, undertray, sidepods, and other aerodynamic surfaces on the competition vehicle.

1.3 Connection to Team Design Goals

The overall vehicle design philosophy for Terps Racing EV emphasizes maximizing aerodynamic downforce while minimizing drag, within the constraints of the FSAE rules. A physical wind tunnel enables the team to:

- Validate CFD predictions against physical flow behavior before committing to manufacturing
- Rapidly compare aerodynamic configurations
- Identify flow separation and wake structures on scale components
- Build institutional knowledge and hands-on aerodynamics experience within the team

1.4 System Requirements

Req. ID	Requirement	Target Value	Verification
SR-01	Test section shall accommodate scale FSAE components	5.740 x 5.740 in (with 0.246 in fillets)	Dimensional
SR-02	Contraction ratio shall produce uniform flow	4.23:1 (min 4:1)	CAD
SR-03	Flow shall be turbulent to simulate real conditions	$Re > 50,000$	Calculated
SR-04	Flow shall remain incompressible	$Ma < 0.3$	Calculated
SR-05	Diffuser half-angle shall prevent separation	$\leq 8^\circ$ equivalent	CAD
SR-06	Tunnel shall support flow visualization	Smoke at 0.7–0.8A	Functional test
SR-07	Velocity shall be controllable via PWM	12.7–30.7 MPH range	Power Calculations
SR-08	Built from 3D-printed and COTS components	Total cost < \$250	~
SR-09	Model blockage ratio below 7%	< 2.30 in ² frontal area	~
SR-10	Flow conditioning for uniformity	Honeycomb + mesh screen	~

2. Understanding of Previous Designs and Design Choices

2.1 Survey of Existing Desktop Wind Tunnels

The design of this wind tunnel was informed by analysis of several existing desktop and educational wind tunnel designs. Key references include publicly available university wind tunnel projects, hobbyist builds, and published guidelines for small-scale wind tunnel design. The team reviewed contraction ratios, diffuser angles, flow conditioning methods, and fan specifications across multiple sources to establish baseline design parameters.

The general topology of a subsonic open-circuit wind tunnel is shown below, illustrating the standard component arrangement used as the starting point for our design:

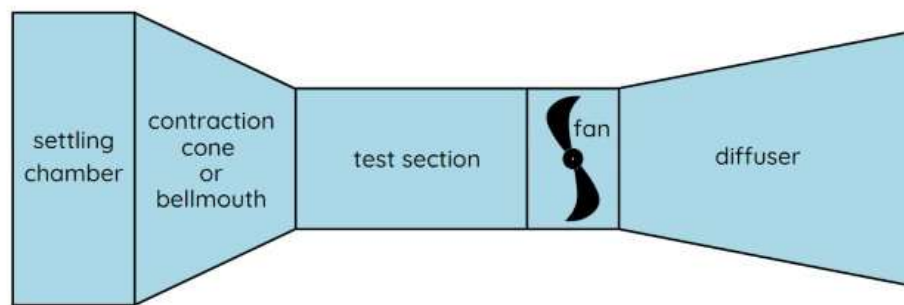


Figure: General open-circuit wind tunnel topology (Source: AzoreCFD)

2.2 Key Design Principles from Literature

- Contraction ratio of 4:1 or higher is standard for small wind tunnels to produce uniform flow and reduce turbulence intensity in the test section.
- Diffuser half-angles should remain below 7–8° to prevent flow separation, which degrades tunnel performance and creates unsteady flow.
- Honeycomb flow straighteners with L/D ratios of 6–12 are recommended. Our current design uses L/D = 4, which is a known compromise due to space constraints.
- A screen or mesh downstream of the honeycomb breaks up residual turbulence structures and improves flow uniformity.
- Open-circuit (suction) tunnels are preferred for desktop scale due to simplicity, cost, and ease of model access.

3. Analysis and CAE on Previous/Reference Designs

Since this is the team's first wind tunnel build, this section presents the analytical framework used to evaluate reference designs and derive the design parameters for our tunnel.

3.1 Continuity Equation Analysis

The continuity equation for incompressible flow, $A_1V_1 = A_2V_2$, governs the velocity relationship between the settling chamber and test section. This was used to size the contraction cone:

$$A_{\text{settling}} = 11.8 \times 11.8 = 139.24 \text{ in}^2$$

$$A_{\text{test}} = 5.740 \times 5.740 \text{ (with fillets)} = 32.90 \text{ in}^2$$

$$\text{Contraction Ratio} = 139.24 / 32.90 = 4.23:1$$

At any given volumetric flow rate Q , the test section velocity is 4.23× the settling chamber velocity. This acceleration through the contraction also reduces the relative turbulence intensity, improving flow quality in the test section.

3.2 Reynolds Number Framework

The Reynolds number determines whether the flow is laminar or turbulent, and is critical for assessing dynamic similarity with full-scale conditions:

$$Re = V \times D_h / \nu$$

where $D_h = 5.838 \text{ in}$ (0.1483 m) is the hydraulic diameter and $\nu = 1.516 \times 10^{-5} \text{ m}^2/\text{s}$ is the kinematic viscosity of air at standard conditions.

At the typical flow viz operating point (0.7–0.8A), $Re \approx 55,000$ –58,000. At maximum power (10A), $Re \approx 134,000$. Both regimes are fully turbulent ($Re \gg 4,000$ for internal flow), confirming that the tunnel produces aerodynamically relevant flow conditions.

3.3 Mach Number Check

For the incompressible flow assumption to hold, the Mach number must remain below 0.3. Even at maximum fan power:

$$Ma = V_{\text{max}} / a = 13.73 / 343 = 0.040$$

This is well below 0.3, confirming that compressibility effects are negligible and standard incompressible flow equations are valid throughout the operating envelope.

3.4 Pressure Drop and Fan Operating Point

The system pressure drop was estimated using loss coefficients for each tunnel component:

Component	Loss Coefficient (K)	Reference Velocity
Honeycomb (1", 1/4" cells)	1.0	Settling chamber
Fine cloth screen	1.5	Settling chamber
Contraction cone	0.05	Test section
Test section friction	0.039	Test section
Curved diffuser	0.2	Test section

The fan's performance under load was modeled using a linear fan curve approximation. At full power, the tunnel operates at approximately 617 CFM, roughly 21% of the fan's free-air rating, due to back-pressure from the honeycomb, screen, and diffuser.

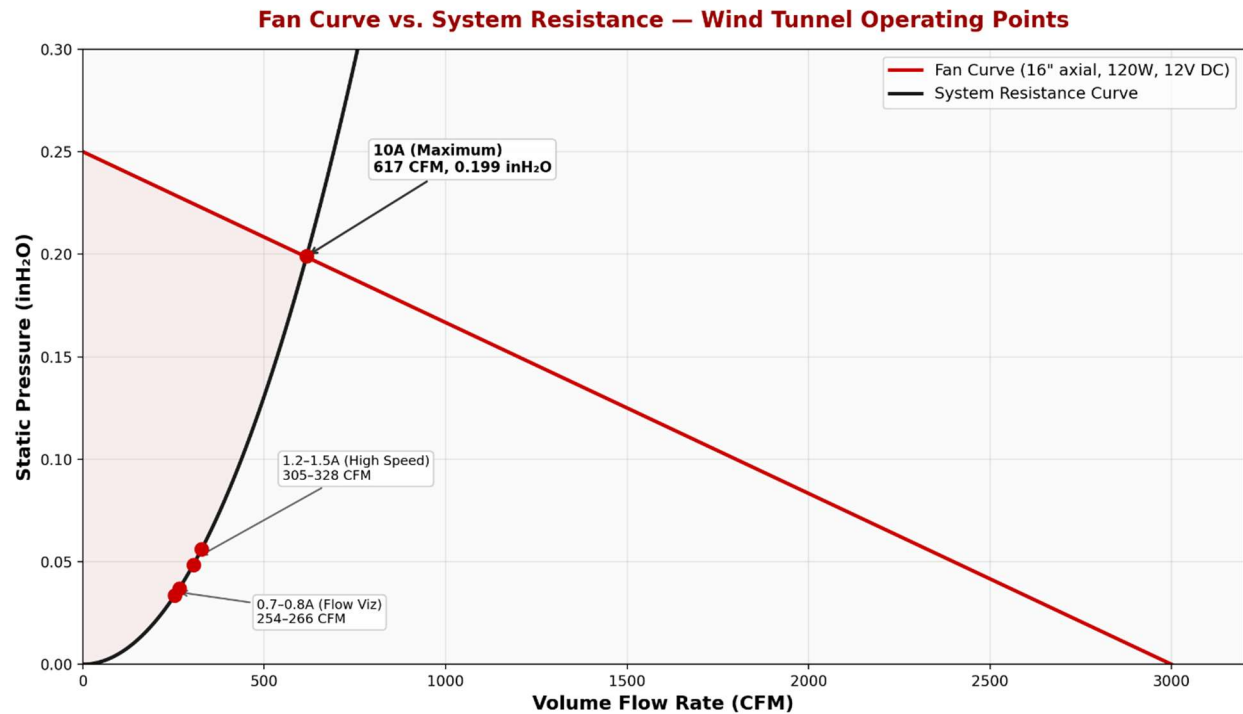


Figure: Fan curve vs. system resistance curve with operating points

4. New Prototype Design

4.1 Overall Configuration

The wind tunnel is an open-circuit, suction-type design with three primary sections: settling chamber with contraction cone, test section, and diffuser with axial fan. The total length in the standard (single test section) configuration is 52.50 inches. A dual test section configuration extends the total length to 63.90 inches.



Figure: Full CAD assembly — isometric rendered view

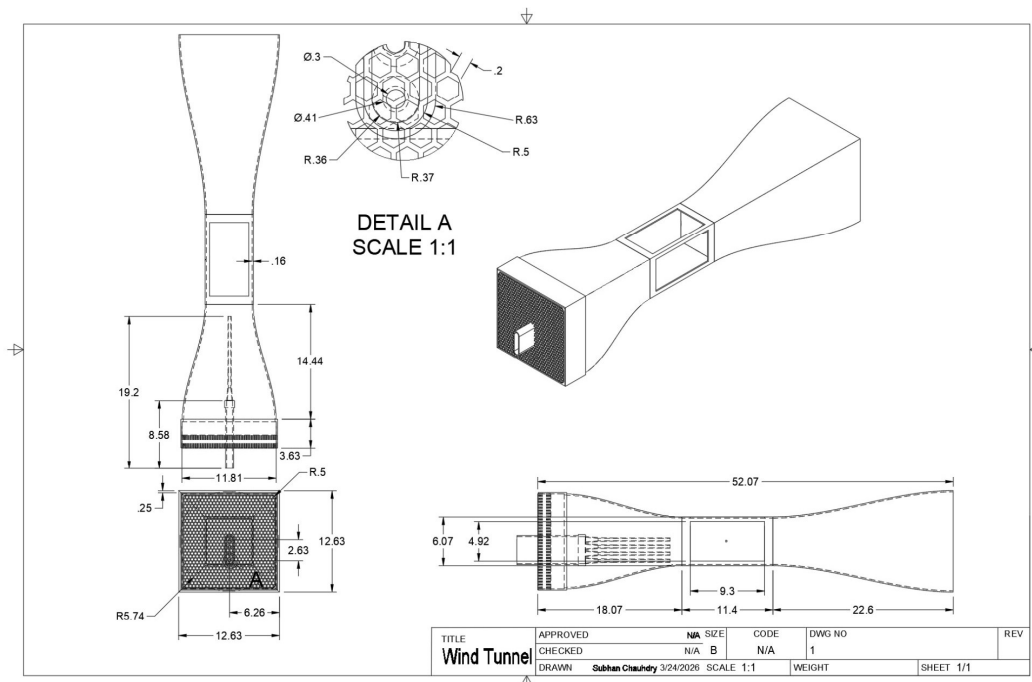


Figure: Complete engineering drawing with dimensions (Drawn: Subhan Chaudhry, 3/24/2026)

4.2 Settling Chamber and Contraction Cone

The settling chamber inlet is 11.8×11.8 inches (139.24 in^2). Flow conditioning is provided by a 1-inch-thick honeycomb with 1/4-inch hexagonal cells followed by a 1-inch gap and a fine cloth mesh screen. The honeycomb straightens the flow by eliminating large-scale swirl and lateral velocity components, while the screen breaks up smaller turbulence structures.

The contraction cone has a total length of 18.267 inches: 3.515 inches of straight settling section followed by 14.752 inches of curved contraction. The curved profile was chosen over a linear contraction to minimize adverse pressure gradients near the walls and reduce the risk of boundary layer separation. The contraction reduces the cross-section from 139.24 in^2 to 32.90 in^2 , yielding a contraction ratio of 4.23:1.



Figure: Aluminum honeycomb flow straightener (1/4" hex cells, 1" thick)

4.3 Test Section

The test section has a cross-section of 5.740×5.740 inches with 0.246-inch radius fillets at each corner. These fillets reduce secondary corner flows that would otherwise create non-uniform velocity distribution. The effective cross-sectional area is 32.90 in^2 and the hydraulic diameter is 5.838 inches (0.1483 m).

The test section length is 11.40 inches, giving a length-to-hydraulic-diameter ratio of approximately 1.95. The test section is printed in black PLA for visual contrast during flow visualization with white smoke.

For the dual test section configuration, a second identical test section is added in series, providing additional testing length or a second measurement station.

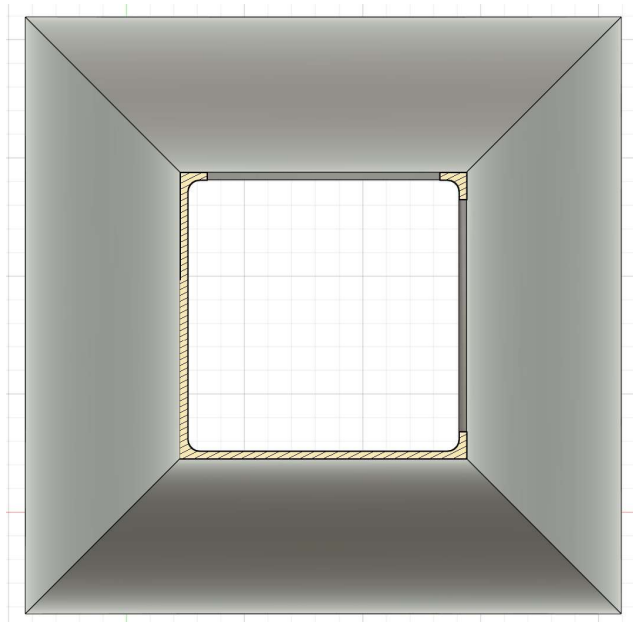


Figure: Test section cross-section CAD view showing corner fillets and contraction-to-test transition

4.4 Diffuser, Fan, and Exit

The diffuser transitions from the 5.740×5.740 inch test section to a 12.68×12.68 inch exit over a length of 22.835 inches. The cross-section transitions from a filleted square to a near-circular profile at the exit (corner fillet arc length of 9.016 inches) to match the 16-inch diameter fan.

The curved diffuser profile was selected over a traditional straight-walled design. The equivalent half-angle is approximately 8.9° , which is slightly above the conventional $7\text{--}8^\circ$ guideline. However, the curved shape produces more favorable pressure gradients than a straight diffuser at the same area ratio, which mitigates separation risk. The diffuser area ratio is 4.03:1.

The fan is a 16-inch axial automotive-style electric fan rated at 120W, 12V DC, 3000 CFM (free-air), and $2000 \pm 10\%$ RPM maximum. Speed is controlled via a PWM motor controller.

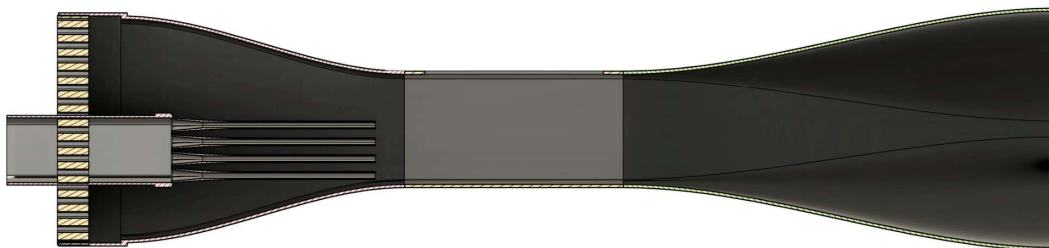


Figure: Side cross-section view showing settling chamber, contraction, test section, and diffuser profiles

5. Analysis and CAE of New Prototype Design

5.1 Operating Envelope

The tunnel was analyzed across five distinct operating modes. The following table summarizes the complete operating envelope:

Mode	Current	Power	RPM	Vel (m/s)	Vel (MPH)	Re
Flow Viz (low)	0.7 A	8.4 W	~824	5.66	12.7	5.54×10^4
Flow Viz (high)	0.8 A	9.6 W	~862	5.92	13.2	5.79×10^4
High Speed (low)	1.2 A	14.4 W	~986	6.77	15.1	6.62×10^4
High Speed (high)	1.5 A	18.0 W	~1063	7.29	16.3	7.14×10^4
Maximum	10.0 A	120.0 W	~2000	13.73	30.7	1.34×10^5

RPM estimates are derived from fan affinity laws ($P \propto n^3$).

5.2 Velocity Calculations

Test section velocity is computed from the volumetric flow rate and test section area: $V = Q / A$. The volumetric flow rate at each operating point is determined from the intersection of the fan curve and the system resistance curve.

At the standard flow visualization setting (12V, 0.7–0.8A), the test section velocity is approximately 5.7–5.9 m/s (12.7–13.2 MPH). At maximum power (12V, 10A), the velocity reaches approximately 13.7 m/s (30.7 MPH).

5.3 Reynolds Number Analysis

Across the operating envelope, Re ranges from approximately 55,000 to 134,000. A full-scale FSAE car at 60 MPH has $Re \approx 2.48 \times 10^6$, roughly $18\times$ higher than the tunnel maximum. This Reynolds number gap means that precise coefficient matching is not achievable, but qualitative flow behavior (separation, reattachment, wake structure) remains representative for design comparison.

5.4 Dynamic Pressure

Mode	Dynamic Pressure (Pa)	Dynamic Pressure (inH ₂ O)
Flow Viz (0.7A)	19.6	0.079
Flow Viz (0.8A)	21.4	0.086
High Speed (1.2A)	28.1	0.113
High Speed (1.5A)	32.6	0.131
Maximum (10A)	115.5	0.464

5.5 Configuration B: Dual Test Section

The dual test section configuration adds a second 11.40-inch test chamber in series (total length 63.90 inches). Analysis shows velocity reduction of approximately 3.8% (from 13.73 to 13.21 m/s at max power), and Reynolds number decreases proportionally from 1.34×10^5 to 1.29×10^5 . The minimal difference occurs because test section friction is small compared to honeycomb/screen and diffuser losses.

5.6 Blockage Analysis

With a test section area of 32.90 in², the maximum allowable model frontal area is 1.64 in² (5% blockage) or 2.30 in² (7% blockage). A 1:10 scale full FSAE car would have 72.6% blockage, which is far too high. The tunnel is intended for testing individual components at scale: wing profiles, endplate configurations, wheel fairings, and similar elements.

6. Prototype Iterations and Narrowing Down Concepts

6.1 Contraction Cone Profile

The contraction cone shape was iterated between a linear taper and a curved (polynomial/spline) profile. The linear taper is simpler to manufacture but produces higher adverse pressure gradients near the downstream end, increasing the risk of boundary layer separation. The curved profile distributes the acceleration more evenly and was selected for the final design.

6.2 Diffuser Geometry

Two diffuser concepts were evaluated: a straight-walled conical diffuser and the current curved diffuser. The straight-walled design at the required area ratio (4.03:1) would have required either a very long diffuser or acceptance of high separation risk. The curved diffuser achieves the same area ratio in 22.835 inches with an equivalent half-angle of 8.9° , but the favorable pressure gradient distribution reduces separation risk compared to a straight wall at the same angle.

The cross-section transition from filleted square to near-circular at the exit was driven by the need to interface with the 16-inch round axial fan.

6.3 Test Section Configuration

The team evaluated single vs. dual test section configurations. The single configuration offers simplicity and slightly higher velocity. The dual configuration enables comparative testing but adds length and marginally reduces velocity (~4%).

6.4 Fan Selection

Several fan options were considered, ranging from computer case fans (80–120mm, low CFM) to larger axial fans. The 16-inch, 120W automotive fan was selected for its high CFM rating relative to cost, PWM controllability, and appropriate diameter to match the diffuser exit.



Figure: Team members assembling the wind tunnel in the Terps Racing workspace

7. Manufacturing and Assembly Plan

7.1 Manufacturing Method

The wind tunnel body is entirely 3D-printed using a Bambu Lab printer. Silver silk PLA is used for the settling chamber, contraction cone, and diffuser; black PLA for the test section (for contrast during flow visualization). Large sections are printed in segments and assembled using alignment features and adhesive.

7.2 Material Selection

Component	Material	Justification
Settling chamber	Silver silk PLA (3D printed)	Aesthetic, structural, low cost
Contraction cone	Silver silk PLA (3D printed)	Complex curved geometry suited to FDM
Test section	Black PLA (3D printed)	Visual contrast for white smoke flow viz
Diffuser	Silver silk PLA (3D printed)	Complex curved transition geometry
Honeycomb	COTS aluminum 1/4" hex, 1" thick	Precision, uniformity, durability
Screen/mesh	Fine cloth netting	Low cost, effective turbulence reduction
Fan	COTS 16" axial, 120W, 12V DC	High CFM, PWM compatible

7.3 Assembly Sequence

1. Print all tunnel sections and fit magnets for attachment
2. Install honeycomb and mesh screen in the settling chamber
3. Attach test section(s) together and tape to seal sections
4. Attach tube to smoke machine
5. Mount fan at diffuser exit with appropriate hardware
6. Connect PWM controller and DC power supply; verify motor operation

7.4 Interface with Vehicle Components

Scale models of FSAE vehicle components are placed in the test section using mounting rods or a sting-type support. Models must be sized to maintain the blockage ratio below 7%. Models can be 3D-printed on the same Bambu Lab printer at appropriate scale for rapid iteration.

8. Validation Plan and Serviceability

8.1 Validation Test Plan

Test	Description	Equipment	Success Criteria
VT-01	Mist Machine testing	Mist maker enclosure	Mist is pulled into test chamber and towards fan
VT-02	Velocity at multiple operating points	Manometer	Within $\pm 15\%$ of calculated values
VT-03	Diffuser separation check	Tuft strips on walls	No sustained tuft reversal
VT-04	Fan speed measurement	Anemometer	RPM within $\pm 15\%$ of estimates
VT-05	Component comparison test	Scale models, smoke/tuft	Distinguishable flow differences
VT-06	Dual test section consistency	Pitot tube in both sections	Velocity difference < 5%

8.2 Validation Test Results to Date

The team has conducted several rounds of testing during development. Initial tests used ultrasonic mist makers (\$21 for 3 units) as a flow visualization medium, but these were replaced with a fog/smoke machine due to insufficient mist density and thickness. Key test results are documented below:

8.2.1 Initial Mist Testing

Early testing used ultrasonic mist fed into the settling chamber. While the mist was visible, it was not dense enough for clear flow visualization. The image below shows vortices forming at the tips of a carbon fiber airfoil during initial mist testing, confirming the tunnel was producing measurable aerodynamic effects even in early development.

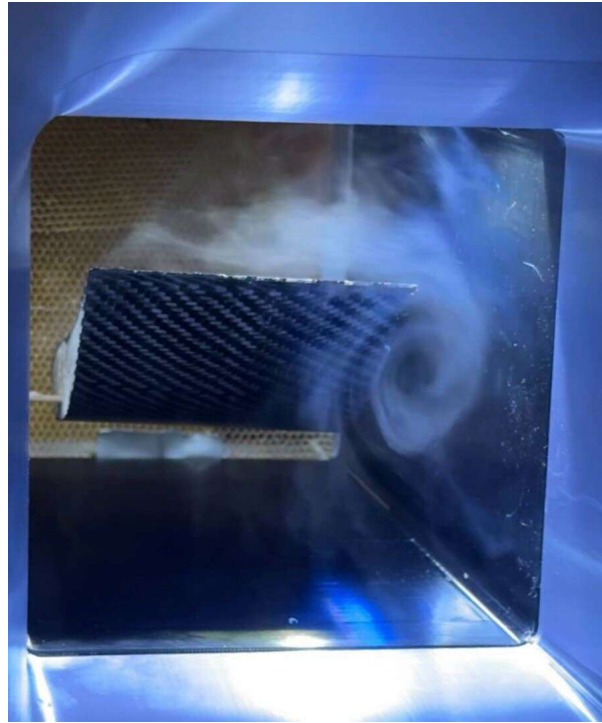


Figure: Initial mist testing showing wingtip vortices on airfoil

8.2.2 Smoke Flow Visualization — Without Honeycomb

Before the honeycomb flow straightener was installed, smoke tests revealed highly turbulent flow in the test section. The image below shows a scale model car in turbulent, unstructured flow.



Figure: Turbulent flow test without honeycomb — unstructured smoke patterns

8.2.3 Smoke Flow Visualization — With Honeycomb (Laminar)

After installing the aluminum honeycomb and mesh screen, flow quality improved dramatically. The images below show smoke flow visualization at the laminar operating point (12V, 0.7–0.8A) with well-defined, parallel streamlines visible over the test models.



Figure: Laminar smoke flow over scale model car with honeycomb installed (12V, 0.7–0.8A)



Figure: Laminar smoke flow over airfoil — cleanest flow visualization result achieved

8.3 Planned Instrumentation Upgrades

- Pitot-static tube with digital manometer for test section velocity measurement
- Fan speed anemometer/tachometer for direct RPM measurement
- Optional: multi-port pressure rake for flow uniformity mapping

8.4 Serviceability

The modular design allows individual sections to be easily connected using magnets, reprinted and replaced if damaged, as well as light for transportation. The honeycomb and screen are removable for cleaning or replacement. The fan is mounted with standard hardware and can be swapped without disassembling the tunnel.

8.5 Known Limitations and Future Improvements

Limitation	Impact	Potential Improvement
Honeycomb L/D = 4 (below 6–12)	Reduced flow straightening	Thicker honeycomb (1.5–2 in) or finer cells
Diffuser equiv. half-angle 8.9°	Slightly elevated separation risk	Extend diffuser length or reduce exit area
Max Re $\sim 1.34 \times 10^5$ (18× below full-scale)	No full dynamic similarity	Accept as limitation; use for qualitative comparison
No force balance	Cannot measure drag/lift directly	Integrate strain-gauge balance
3D print surface roughness	May trip boundary layer early	Sand and coat interior surfaces

9. Bill of Materials

Item	Description	Qty	Unit Cost	Total	Source
Silver Silk PLA	Settling chamber, contraction, diffuser	~2 rolls	~\$25	~\$50	Bambu / Amazon
Black PLA	Test section(s)	~0.5 roll	~\$20	~\$20	Bambu / Amazon
Axial Fan	16", 120W, 12V DC, 3000 CFM	1	\$50	\$50	Amazon
Honeycomb	1/4" hex, 1" thick, aluminum	1	\$40	\$40	Amazon / McMaster
Smoke Machine	Fog generator for flow viz	1	\$30	\$30	Amazon
PWM Controller	DC motor speed controller	1	\$12	\$12	Amazon
DC Power Supply	12V bench supply (team-owned)	1	N/A	\$0	Team inventory
Cloth Netting	Turbulence screen mesh	1	~\$5	~\$5	Fabric / Amazon
Mist Makers (replaced)	Ultrasonic mist generators (3x)	3	\$7	\$21	Amazon
Fasteners & Adhesive	Hardware, CA glue, tape	1 lot	~\$10	~\$10	Hardware store

Estimated Total Project Cost: ~\$238

Note: The DC power supply is existing team equipment. 3D printing costs are estimated based on filament usage at approximately 500–700g per major section.

10. Complete Geometry and Dimensions Summary

Parameter	Value
Overall length (Config A)	52.50 in
Overall length (Config B, dual test)	63.90 in
Settling chamber inlet	11.8 × 11.8 in (139.24 in ²)
Honeycomb	1" thick, 1/4" hex cells, L/D = 4
Screen	Fine cloth mesh, ~1" after honeycomb
Contraction total length	18.267 in
Contraction straight section	3.515 in
Contraction curved section	14.752 in
Contraction ratio	4.23:1
Test section cross-section	5.740 × 5.740 in (0.246 in fillets)
Test section area	32.90 in ² (0.02122 m ²)
Test section length	11.40 in
Hydraulic diameter	5.838 in (0.1483 m)
Diffuser length	22.835 in
Diffuser inlet	5.740 × 5.740 in (filleted square)
Diffuser exit	12.68 × 12.68 in (9.016 in corner arc)
Diffuser area ratio	4.03:1
Diffuser equiv. half-angle	8.9°
Fan	16", 120W, 12V DC, 3000 CFM, 2000 RPM

11. References and Acknowledgments

The team would like to express gratitude to Terps Racing Electric Vehicle Team for the opportunity and resources to develop this mini wind tunnel. Furthermore, the following articles, documents and videos were used as references for design considerations and improvements.

References

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