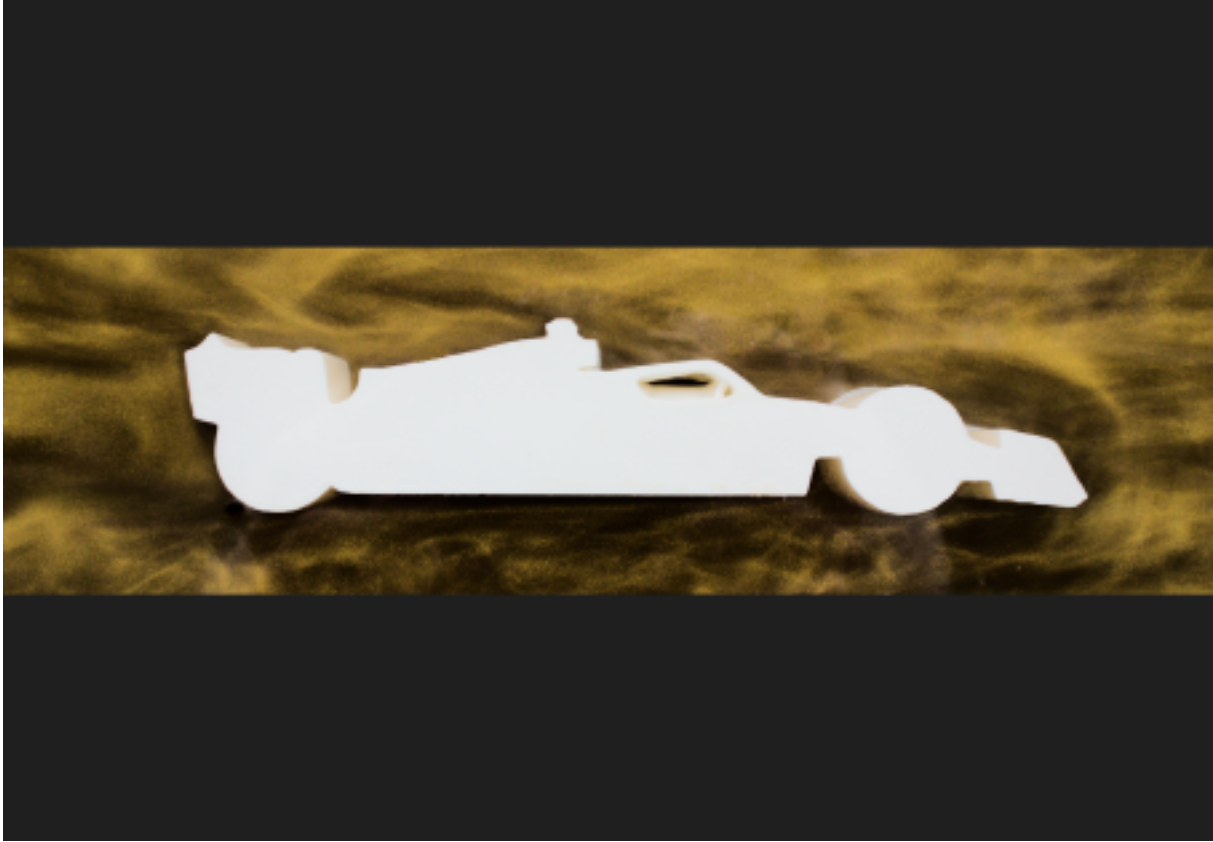




# 2D Flow over F1 Car in Water Tunnel

**MCEN 5151: Flow Visualization**

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Team First Assignment

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# 1 Introduction

The image of two dimensional flow over the side profile of a 1:32 scale Formula 1 race car in a water tunnel visualizes how cutting edge racing technology interfaces with the fluid dynamics themselves, specifically stagnation zones, locally separated shear areas, and boundary layers. This photograph was taken in accordance with the Team First assignment, utilizing the visualization principles outlined in MCEN 5151: Flow Visualization. The primary objective was to capture the flow phenomena around an F1 car to evaluate the boundary layers and visualize turbulence around the vehicle. Initially conceived as the flow around a cow, the change to the F1 car was made due to its more intricate design and relevant fluid phenomena. Artistically, the photograph bridges the complex beauty of aerodynamic flow with underlying drag implications, creating a contrasting, yet fascinating image.

## 2 Flow Phenomena

To analyze the fluid dynamics within the image, identification of the main flow phenomena is crucial.

Just to the right of the nose of the F1 car is a stagnation zone, visualized in Figure 1. A stagnation zone is an area in a flow where the velocity of the fluid drops to near-zero due to the geometry in its flow path, creating a localized peak in static pressure and forcing faster moving fluid around it. This is what creates the golden ring seen in the image which outlines the stagnation zone.

Furthermore, an attached boundary layer can be identified when looking at the bottom surface of the F1 car outline. As shown in Figure 1, there is a boundary layer of the flow attached to the bottom surface because of the smooth and continuous geometry of the bottom of the F1 car. At the bottom of the car, the flow speed is zero, but as the flow gets further from the base of the car it begins to speed up until it hits the freestream velocity of the surrounding fluid, which is seen in the image when there is a transition from the black region to the golden region in the flow beneath the F1 car.

Another identifying feature of this flow is the locally separated shear areas, of which there are three main ones, outlined in Figure 1. A locally separated shear area is a thin region of high velocity shear that forms when fluid detaches from a solid surface in a specific, localized area due to an adverse pressure gradient or a sharp geometric edge.

Finally, the wake follows behind the model and is a form of the locally separated shear areas, but is unique in the fact that the flow inside of the separated shear areas has near zero velocity due to the geometry of the car. It will be discussed and analyzed further in the following sections.

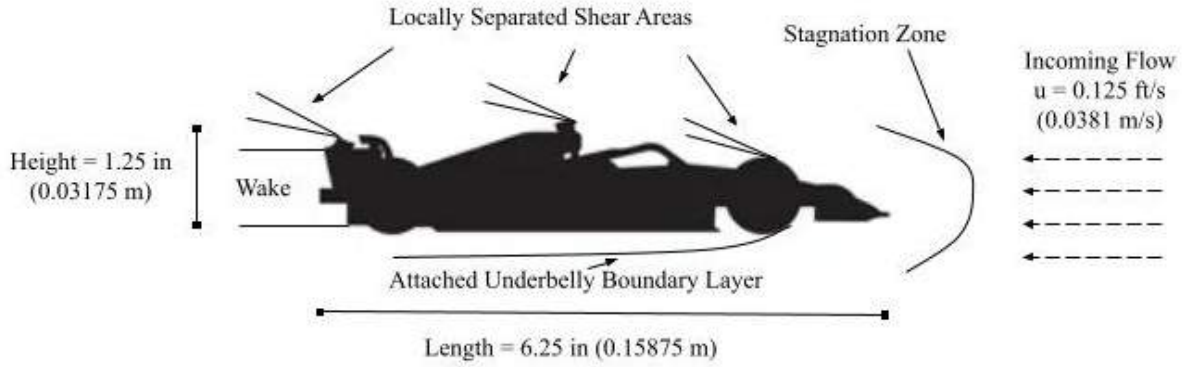


Figure 1: Flow Around F1 Car Analysis Diagram

To quantitatively characterize the hydrodynamic phenomena around the 1 : 32 scale F1 chassis, fluid properties for water at  $T = 20^\circ\text{C}$  ( $\rho = 998 \text{ kg/m}^3$ ,  $\nu = 1.004 \times 10^{-6} \text{ m}^2/\text{s}$ ,  $\sigma = 0.0728 \text{ N/m}$ , and  $g = 9.81 \text{ m/s}^2$ ) are evaluated alongside the experimental model dimensions. Because the chassis contains multiple aerodynamic elements, including the front wing, cockpit, side structures, rear wing, and underbody, the resulting flow is inherently three-dimensional and involves interacting separated flow structures rather than a single canonical geometry [1, 2].

- Characteristic Model Length:  $L = 6.25 \text{ in} = 0.15875 \text{ m}$
- Characteristic Model Height:  $H = 1.25 \text{ in} = 0.03175 \text{ m}$
- Free-Stream Flow Velocity:  $U_\infty = \frac{1 \text{ ft}}{8 \text{ s}} = 0.125 \text{ ft/s} = 0.0381 \text{ m/s}$

## 1. Reynolds Number ( $Re_L$ )

The length-based Reynolds number quantifies the ratio of inertial forces to viscous forces and provides the primary scaling parameter for the external flow around the chassis:

$$Re_L = \frac{U_\infty L}{\nu} = \frac{(0.0381 \text{ m/s})(0.15875 \text{ m})}{1.004 \times 10^{-6} \text{ m}^2/\text{s}} = 6.02 \times 10^3$$

The resulting  $Re_L \approx 6.02 \times 10^3$  places the experiment in a low-Reynolds-number regime relative to full-scale automotive and Formula 1 aerodynamics. Consequently, viscous effects exert a substantially greater influence on the model-scale flow than they would for a full-scale vehicle. This has particular importance for the aerodynamic surfaces, where boundary-layer state and separation location can change significantly with Reynolds number. Experimental

investigations of racing-car front wings have demonstrated strong Reynolds-number sensitivity in both force production and boundary-layer transition [2]. The present value should therefore be interpreted as a model-scale Reynolds number rather than as a direct representation of the full-scale Formula 1 flow.

A second Reynolds number based on model height is useful because the thickness of the chassis is substantially smaller than its total length:

$$Re_H = \frac{U_\infty H}{\nu} = \frac{(0.0381 \text{ m/s})(0.03175 \text{ m})}{1.004 \times 10^{-6} \text{ m}^2/\text{s}} = 1.20 \times 10^3$$

The height-based Reynolds number is approximately five times smaller than the length-based value. This difference illustrates why small geometric features on the chassis can exhibit stronger viscous influence than the overall vehicle-scale wake. The flow around the front and rear aerodynamic elements can therefore separate at sharp edges and generate shear layers that subsequently roll into coherent vortical structures downstream. Racing-car aerodynamic studies have shown that interactions between multiple body components produce complex three-dimensional vortex systems rather than the isolated wake associated with a simple bluff body [1].

## 2. Strouhal Number ( $St$ ) & Vortex Shedding Frequency ( $f$ )

The Strouhal number characterizes the relationship between a characteristic unsteady frequency, the flow velocity, and the relevant geometric length scale. Because no time-resolved measurements were obtained for the present image, a canonical bluff-body value of  $St_H \approx 0.21$  is used as a first-order estimate for the dominant wake-shedding frequency:

$$St_H = \frac{fH}{U_\infty}$$

$$f = \frac{St_H U_\infty}{H} = \frac{(0.21)(0.0381 \text{ m/s})}{0.03175 \text{ m}} = 0.252 \text{ Hz}$$

The corresponding shedding period is

$$T_s = \frac{1}{f} = \frac{1}{0.252 \text{ Hz}} = 3.97 \text{ s}$$

The estimated  $T_s \approx 3.97 \text{ s}$  indicates that a dominant large-scale wake structure would convect through a cycle on a time scale comparable to the approximately 4.17 s required for fluid to travel one model length. Alternate vortex shedding and strong wake unsteadiness have been experimentally observed behind racing-car wings and other bluff aerodynamic geometries [3, 4]. The value  $St_H = 0.21$ , however, should be treated as an order-of-magnitude

estimate rather than a measured property of this specific F1 chassis because Strouhal number depends on geometry, Reynolds number, separation behavior, and blockage conditions [4, 5].

The corresponding dimensionless shedding frequency based on the full model length is

$$St_L = \frac{fL}{U_\infty} = \frac{(0.252 \text{ Hz})(0.15875 \text{ m})}{0.0381 \text{ m/s}} \approx 1.05$$

The difference between  $St_H$  and  $St_L$  demonstrates the importance of selecting a physically appropriate characteristic length. The rear-wing height or another transverse wake dimension is more representative of the assumed shedding scale than the full vehicle length. The estimated frequency therefore provides a useful temporal scale for the wake but should not be interpreted as a direct measurement from the photograph.

### 3. Underbody Laminar Boundary Layer Thickness ( $\delta_L$ )

As a first-order estimate, the underbody may be approximated as a smooth flat plate with a laminar boundary layer developing from the leading edge. The classical Blasius solution gives the boundary-layer thickness at  $x = L$  as approximately

$$\delta_L \approx \frac{5L}{\sqrt{Re_L}} = \frac{5(0.15875 \text{ m})}{\sqrt{6.02 \times 10^3}} \approx 0.0102 \text{ m} = 10.2 \text{ mm}$$

The estimated boundary-layer thickness is approximately

$$\frac{\delta_L}{H} = \frac{0.0102 \text{ m}}{0.03175 \text{ m}} \approx 0.321$$

or approximately 32% of the total vehicle height. This indicates that viscous effects can occupy a substantial fraction of the vertical flow domain beneath the model. The calculation is an idealized estimate because the actual chassis contains curvature, sharp edges, pressure gradients, wheels, wings, and a moving wake, all of which violate the assumptions of the zero-pressure-gradient flat-plate solution. Nevertheless, it provides a useful scale for assessing the relative thickness of the near-wall viscous region. Standard boundary-layer theory predicts that the laminar boundary layer grows approximately as  $\delta/x \propto Re_x^{-1/2}$ , consistent with the strong relative boundary-layer growth expected at this model-scale Reynolds number [6].

## 3 Visualization Technique

The execution of the flow visualization technique relied on extensive setup and the use of rheoscopic fluid. As depicted in Figure 2, a water tunnel, filled using a house spigot, moved water across the face of the black acrylic sheet separating the front fifth of the tank from the right side of the image to the left side of the image. Three "flow straighteners" can be

seen in the tank (transparent rectangles), which were utilized to transition the flow from a turbulent state coming from the outlet of the pump (see bottom right of photo) to a laminar, horizontal state. From there, the flow continued past the "test section", which is where the F1 car is located, and into the pipe connected to the inlet of the pump through the black hose. For water damage mitigation, the 40 gallon tank was operated outdoors on an overcast day. Also as pictured in Figure 2, the camera was placed with the lens at the same height as the F1 car, with the tripod located one foot from the tank. To visualize the flow, a special type of particle tracking was utilized: mica powder. Approximately 20 g of gold mica powder was spread evenly throughout the water in the tank, creating a rheoscopic fluid, which is a specialized liquid that makes internal currents, swirls, and turbulence visible as it moves. The mica powder has minuscule flakes that align with the direction of the flow in the water, causing uniform reflective properties where the flow direction is uniform. Combining the mica powder and previously described setup (and a little bit of headache) resulted in the final image.



Figure 2: Water Tunnel and Camera Setup

## 4 Photographic Technique

This image was captured using A 2013 Canon eos Rebel T3i DSLR camera, resulting in an uncropped resolution of  $5198 \times 3462$  pixels. The image was taken using a 32 mm focal length, and operational exposure settings were set to ISO 800, an aperture of  $f/10.0$ , and a shutter speed of  $1/50$ s.

The object-to-lens distance was approximately 1 ft (0.3048 m), yielding a physical field of view measuring roughly 8.75 in (0.2222 m) horizontally by 6.25 in (0.1588 m) vertically. The spatial framing was subsequently adjusted during post-processing in darktable. As shown in Figure 3, regions of flow above and below the affected zones were cropped out to minimize distractions and minimize glare. To bring out the gold zones in the flow, the tone curve was adjusted to make the dark colors darker, the middle tones brighter, and the bright colors darker. This allowed the gold flow zones to be highlighted without blowing highlights from the white F1 car in the image.



Figure 3: Original, Unedited Team First Photo

## 5 Artists Statement

This image illustrates the beauty in a flow that is at first glance something purely technical. While aerodynamic flow around a vehicle is commonly viewed from an empirical

perspective, this image incorporates the beauty of how the water and mica powder streak, swirl, and collide to create a wonder-inducing image. At the same this photo can be analyzed to determine valuable aerodynamic force data without requiring extensive computational resources in an FEA simulation.

Future work will incorporate continued improvement with a DSLR camera and exposure techniques to limit glare.

Further development of this study could explore a multitude of other shapes, a few of which were tried when taking this photo. The University of Colorado Buffaloes logo was used for this image, creating unique flow characteristics in the surrounding flow but could not be included in this report due to copyright law.

## References

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