Car Window's Effect on Drag

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I. ABSTRACT

The objective of this lab is to measure the difference between drags for a car with its windows rolled all the way up versus a car with its windows rolled completely down. To measure the difference, a 3D-printed model of a Mazda Mx5 was used. For measuring with the windows rolled down, the window part of the model was left hollow, while for measuring with the windows all the way up, clay was used to block any air from getting trapped in the model. Both designs were tested at 5 m/s, 12 m/s, and 20 m/s. Data was collected using a force balance that was calibrated with multiple weights, resulting in an output in the form of voltage, which was then used to find the drag at each speed for each model. The results of the experiment showed a decrease in drag at the lowest free stream velocity, and an increase in drag at 20 m/s (44.74 mph) which was more than twice that of the 12 m/s trial, portraying an increase in drag with increasing velocity and windows being down.

II. INTRODUCTION

As automobiles have become an essential component of our daily lives, it is a constant strive to create vehicles with better aerodynamic efficiency. One way to achieve this is by testing the effects of rolling down car windows on the car's drag. This information is particularly important because many people prefer to roll down their windows instead of using air conditioning to save on fuel. By understanding the impact of open windows on a car's aerodynamics, it is possible to optimize the vehicle's fuel efficiency, which can reduce carbon emissions and save consumers money on fuel. In addition, it is crucial to consider that open windows can cause excessive drag at higher speeds, which may compromise the car's stability and handling, ultimately affecting safety.

III. METHODOLOGY

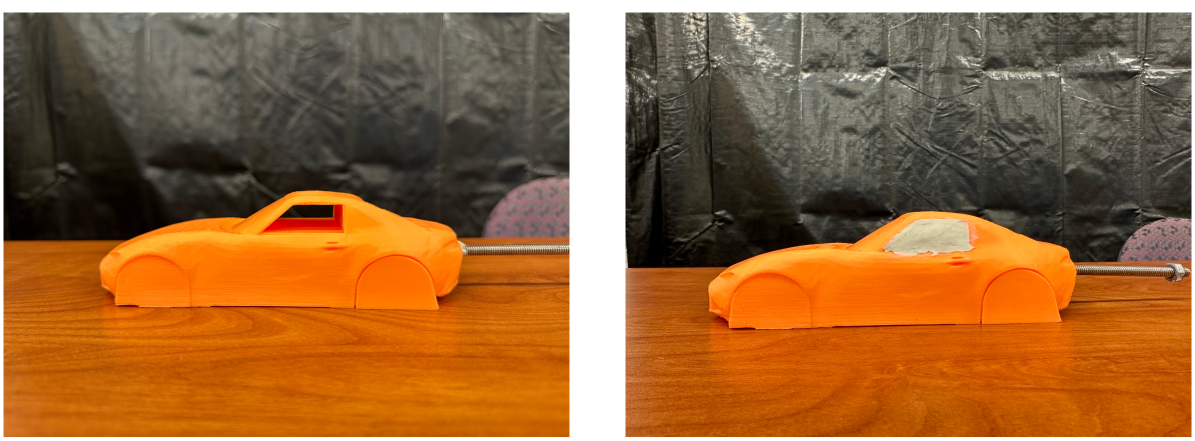

Figure 1: (Left) Model with no window (Right) Model with clay as the window

The experiment was carried out in a subsonic wind tunnel measuring 2x2 ft, using a 3D printed scale model of a Mazda Mx5. The model was about 200 mm in length and had a cross-sectional area of 2.19 in^2, with a scale ratio of approximately 20:1. The surface finish of the model was kept untreated in order to provide a rougher surface for the flow to travel along. This helped to increase the effective Reynolds number of the airflow by creating boundary layer turbulence similar to trip strips on the leading edge of airfoils. In Figure 1, the model on the left exhibits a window-shaped hole in a location that closely resembles a real car. To keep the model's consistency, the image on the right portrays the same car model filled with clay to simulate a rolled-up window. This ensured that the mounting position did not affect the test results, as well as any 3D printing differences.

Before starting the trial, the ambient pressure (P_{atm}) and temperature (T_{atm}) of the room were measured. Using these values and the free-stream velocities, the dynamic pressures (q) were calculated to help us calibrate the speed inside the wind tunnel as shown in Table 1.

Constants:	Ambient Pressure (in-Hg)	30.13	Ambient Temperature (F°)	74.93
Variables:	Free-Stream Velocity (m/s)	5	12	20
	Frequency (Hz)	7.5	16.7	26.9
	Dynamic Pressure (in-H_2O)	0.0604	0.3478	0.9663

Table 1: Recorded ambient values before experimentation started

For data acquisition, a drag calibration was done prior to conducting any trial. Then, a lift and drag balance was utilized, which involved performing a gravity tare before each trial. The experiment consisted of testing two window conditions, fully rolled-up and fully rolled-down, at three distinct free-stream velocities (5, 12, and 20 m/s). By comparing the calculated drag values using the outputs taken from the lift and drag balance, the drag increase for rolling car windows down can be calculated and a rough estimate can be made for a full-size car model.

IV. RESULTS AND DISCUSSION

To convert the voltage outputs from the lift and drag balance, equation [1] was used. The calculated average drag on the model at each condition is visible in *Figure 1*. When looking at the figure, it is clear that having the windows open at lower freestream velocities has a very small impact on the drag, essentially negligible. However, at 20 m/s, there is a noticeable increase in drag when the windows are in the down position visible in *Figure 1*.

$$D = -k_d(V_m - V_o) \quad \text{Eq. [1]}$$

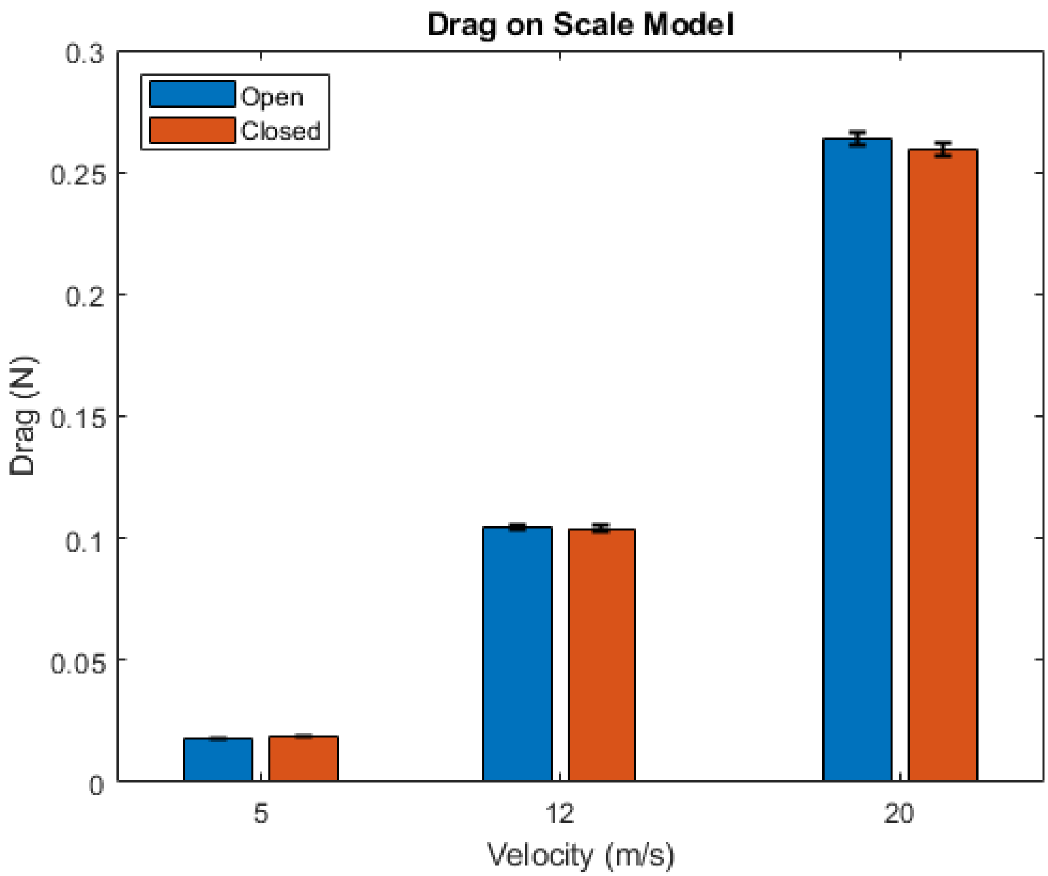

Figure 1: Shows the calculated drag at each freestream velocity and window condition.

Looking to *Table 2,* the total change in drag values resulting from the window position are tabulated. The table shows a decrease in drag by over 5% at the 5 m/s freestream velocity when the windows are down. This could be due to the pocket being created causing the flow to become turbulent earlier as it passes over the model. This turbulent flow is more energetic meaning its region of flow separation is less due to increased flow mixing, creating less drag. The largest increase in drag is seen at the 20 m/s trial, where there was a 1.698% increase in total drag. This is a rather small increase considering the large increase in free stream velocity, but is more than twice the change seen in the 12 m/s trial. Understanding how much the change increased from a relatively small increase in freestream velocity, shows the potential impact the window position plays in changing the drag at higher velocities.

Table 2: Calculated drag of model for each window condition

Free Stream Velocity (m/s)	Drag with windows up (N)	Drag with windows Down (N)	Percent Change (%)
5	0.0190 ±0.0002	0.0179 ±0.0002	-5.789
12	0.1040 ±0.0010	0.1047 ±0.0010	0.673
20	0.2637 ±0.0026	0.2593 ±0.0026	1.697

$$C_D = \frac{D}{q*S} \qquad \text{Eq. [2]}$$

Equation [2] was used to calculate the coefficient of drag. The characteristic area S was assumed to be a perfect rectangle, using the max width and height of the model to calculate the area. The dynamic pressure q was calculated before the trials, and used to acquire the desired freestream velocity in the wind tunnel. Looking to *Table 3*, the coefficient of drag decreased with the increasing free stream velocity, and similar coefficients of drag are seen despite the window position. Once again, the 5 m/s trials had the largest difference, likely due to the primarily laminar flow separating at the windows, earlier on the model, creating a more energetic flow allowing for faster flow mixing and decreased drag.

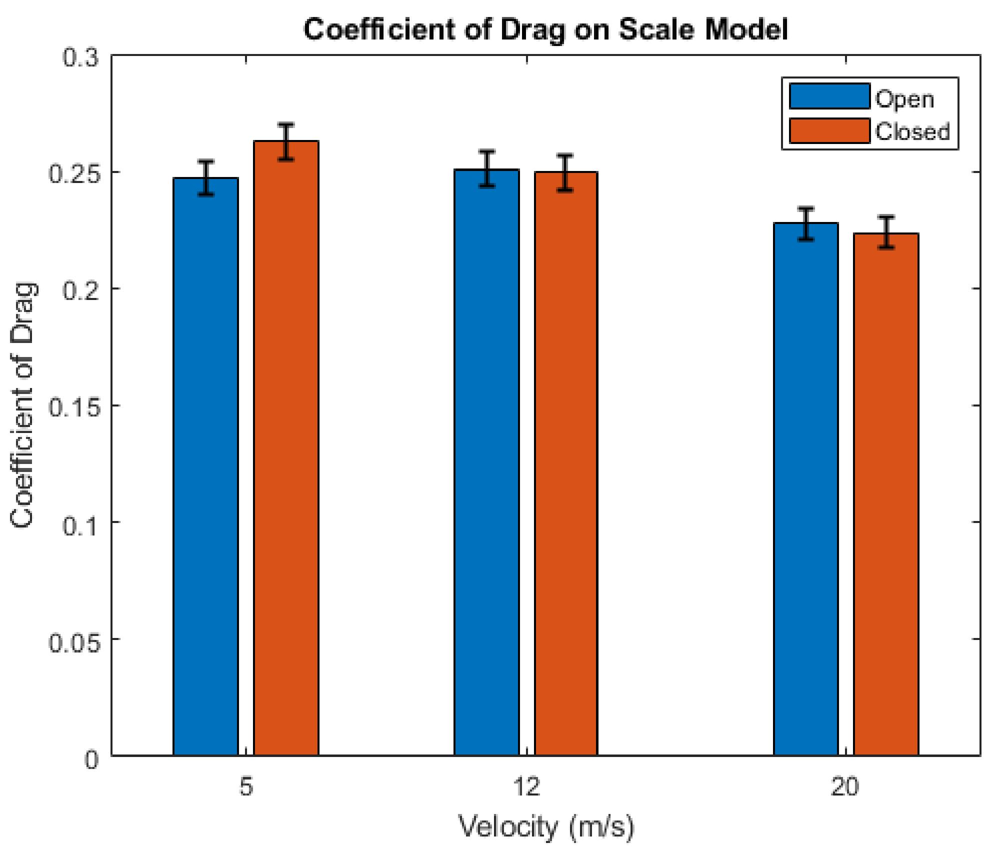

Figure 2: Compares the coefficient of drags for each window condition at each free stream velocity

Table 3: Coefficients of drag for each free stream and window condition

Free Stream Velocity (m/s)	Coefficient of Drag w/ Windows Open	Coefficient of Drag w/ Windows Down
5	0.2487 ±0.0070	0.2643 ±0.0074
12	0.2524 ±0.0071	0.2508 ±0.0071
20	0.2289 ±0.0064	0.2251 ±0.0063

In *Table 4*, the Reynolds numbers were calculated for each of the free stream velocities tested by using equation [3]. The air density (ρ_∞) and dynamic viscosity (μ_∞) obtained from atmospheric conditions, free stream velocity (V_∞) corresponds to the free stream velocities of 5, 12, and 20 m/s, and the characteristic linear dimension chosen as the length of the car model (L) were used.

$$Re = \frac{\rho_\infty V_\infty L}{\mu_\infty} \qquad \text{Eq. [3]}$$

The obtained Reynolds numbers provided insights into the flow regime around the car model and can help explain the experimental results. At lower Reynolds numbers (6.691×10^4, 1.6058×10^5), the flow around the vehicle is primarily laminar, with relatively smooth air flow motion. In this flow regime, the drag experienced by the car model is primarily influenced by viscous forces, which could explain the lack of significant differences in drag between the open and closed window configurations. As the Reynolds number increased (2.6763×10^5), the flow around the car model became increasingly turbulent. In this flow regime, the drag experienced by the car is influenced by both viscous and pressure forces due to flow separation and turbulence. This transition to a more turbulent flow regime could be responsible for the increased drag observed for the car model with open windows at the higher free stream velocity of 20 m/s. The open windows have contributed to the development of turbulence inside the cabin, which disrupted the laminar flow around the vehicle and led to an increase in drag.

Table 4: Reynolds numbers for various free stream velocities

Velocity (m/s)	Reynolds Number (10^5)
5	0.6691 ±0.0150
12	1.6058 ±0.0361
20	2.6763 ±0.0602

V. ERROR ANALYSIS

Throughout this experiment, care was taken to try and minimize the amount of error present within the data. This includes standing clear of the tunnel inlet to prevent flow distortion, having multiple people ensure the model was being held horizontally, and averaging all collected data over a longer period of time. Experimental error is inevitable however, so an uncertainty of 1% was used for all measured values including, pressure, temperature, force, and area. These errors were propagated through the calculations for the coefficient of drag and Reynolds number for all six tests using the standard error propagation method shown in *Equations 4 - 9.* The average uncertainty between all six runs was found to be ± 0.0069 and $\pm 3.7121\times10^{3}$ respectively.

$$\sigma_{\rho} = \sqrt{\left(\frac{\delta\rho}{\delta P}\cdot\sigma_{P}\right)^{2} + \left(\frac{\delta\rho}{\delta T}\cdot\sigma_{T}\right)^{2}} \qquad \text{Eq. [4]}$$

$$\frac{\delta\rho}{\delta P} = \frac{1}{RT} \qquad \frac{\delta\rho}{\delta T} = \frac{-P}{RT^{2}} \qquad \text{Eq. [5]}$$

$$\sigma_{Cd} = \sqrt{\left(\frac{\delta Cd}{\delta D}\cdot\sigma_{D}\right)^{2} + \left(\frac{\delta Cd}{\delta q}\cdot\sigma_{q}\right)^{2} + \left(\frac{\delta Cd}{\delta S}\cdot\sigma_{S}\right)^{2}} \qquad \text{Eq. [6]}$$

$$\frac{\delta Cd}{\delta D} = \frac{1}{qS} \qquad \frac{\delta Cd}{\delta q} = \frac{-D}{q^{2}S} \qquad \frac{\delta Cd}{\delta S} = \frac{-D}{qS^{2}} \qquad \text{Eq. [7]}$$

$$\sigma_{Re} = \sqrt{\left(\frac{\delta Re}{\delta\rho}\cdot\sigma_{\rho}\right)^{2} + \left(\frac{\delta Re}{\delta V}\cdot\sigma_{V}\right)^{2} + \left(\frac{\delta Re}{\delta\mu}\cdot\sigma_{\mu}\right)^{2} + \left(\frac{\delta Re}{\delta L}\cdot\sigma_{L}\right)^{2}} \qquad \text{Eq. [8]}$$

$$\frac{\delta Re}{\delta\rho} = \frac{LV}{\mu} \qquad \frac{\delta Re}{\delta V} = \frac{L\rho}{\mu} \qquad \frac{\delta Re}{\delta\mu} = \frac{-LV\rho}{\mu^{2}} \qquad \frac{\delta Re}{\delta L} = \frac{V\rho}{\mu} \qquad \text{Eq. [9]}$$

VI. CONCLUSION

This experiment has demonstrated the importance of considering window position when examining the aerodynamics and fuel consumption of a vehicle. The results showed that driving with windows open at higher speeds can lead to increased drag and fuel consumption, suggesting that it might be more fuel-efficient to drive with windows closed and A/C on in such situations. The increase in drag observed at a free stream velocity of 20 m/s for the car model with windows open was caused by the air turbulence generated inside the car's cabin. This turbulence disrupted the smooth airflow around the vehicle, leading to increased resistance and energy consumption. Another factor potentially contributing to the increased drag was the role of the rear windshield. In certain conditions, the rear windshield can act as a parachute, exacerbating the drag experienced by the vehicle. This parachute effect is particularly prominent at higher speeds, as the increased airflow and turbulence generated inside the cabin contribute to the formation of the low-pressure area behind the vehicle. Consequently, this low-pressure area acts as a suction force, pulling the car backward and increasing the drag experienced by the vehicle. In contrast, at lower velocities, the difference in drag was insignificant, possibly due to the reduced impact of internal air turbulence.

Future research on the impact of window position effects on vehicle aerodynamics and fuel consumption can be enhanced by considering various factors. These include evaluating the effects of partially opened windows, using different vehicle models with various shapes, and analyzing the fuel consumption of a car's air conditioning system by fuel types, such as gasoline, diesel, hybrid, and electric vehicles.

VII. REFERENCES

[1] Embry-Riddle Aeronautical University Department of Aerospace Engineering, AE 315 Lab 3 Manual: Drag on Different Objects

VIII. APPENDIX

$$D = -k_d(V_m - V_o) \quad [1]$$

$$C_D = \frac{D}{q*S} \quad [2]$$

$$Re = \frac{\rho_\infty V_\infty L}{\mu_\infty} \quad [3]$$

$$\sigma_\rho = \sqrt{\left(\frac{\delta\rho}{\delta P}\cdot\sigma_P\right)^2 + \left(\frac{\delta\rho}{\delta T}\cdot\sigma_T\right)^2} \quad [4]$$

$$\frac{\delta\rho}{\delta P} = \frac{1}{RT} \qquad \frac{\delta\rho}{\delta T} = \frac{-P}{RT^2} \quad [5]$$

$$\sigma_{Cd} = \sqrt{\left(\frac{\delta Cd}{\delta D}\cdot\sigma_D\right)^2 + \left(\frac{\delta Cd}{\delta q}\cdot\sigma_q\right)^2 + \left(\frac{\delta Cd}{\delta S}\cdot\sigma_S\right)^2} \quad [6]$$

$$\frac{\delta Cd}{\delta D} = \frac{1}{qS} \qquad \frac{\delta Cd}{\delta q} = \frac{-D}{q^2 S} \qquad \frac{\delta Cd}{\delta S} = \frac{-D}{qS^2} \quad [7]$$

$$\sigma_{Re} = \sqrt{\left(\frac{\delta Re}{\delta\rho}\cdot\sigma_\rho\right)^2 + \left(\frac{\delta Re}{\delta V}\cdot\sigma_V\right)^2 + \left(\frac{\delta Re}{\delta\mu}\cdot\sigma_\mu\right)^2 + \left(\frac{\delta Re}{\delta L}\cdot\sigma_L\right)^2} \quad [8]$$

$$\frac{\delta Re}{\delta\rho} = \frac{LV}{\mu} \qquad \frac{\delta Re}{\delta V} = \frac{L\rho}{\mu} \qquad \frac{\delta Re}{\delta\mu} = \frac{-LV\rho}{\mu^2} \qquad \frac{\delta Re}{\delta L} = \frac{V\rho}{\mu} \quad [9]$$