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Testing Ground-effect Aerodynamics on a Scaled F1 Car

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Testing Ground Effect Aerodynamics on a Scaled F1 Car

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Abstract

Formula-1 (F1) racing cars aerodynamic effects are mainly controlled by the body contours and other aerodynamic elements such as over-body wings. Over-body wings tend to force the car downwards but would increase the drag force on the car. This capstone project investigated the ground effects on a scaled F1 car by testing the down force and drag force with and without ground effects. To meet the objectives, an 8.8 feet-long (2.93 m) wind tunnel was built by the team having a 6 × 6 sq.in (3.34 m^2) cross-section testing chamber running air at an approximate speed of 34 miles per hour (mph) which simulates an actual speed of 150 mph in actual racing environment. Six revisions of ground effect structures were 3D printed to test ground effect improvements on the scaled F1 car inside the wind tunnel. The conceptual structure design was based on creating low pressure vacuum region between the bottom of the car and the ground by using venture gates and side skirts. The vacuum in turn would suck the car down as close to the ground as possible, which will in turn keep the wheels firmly pressed into the floor. Five revisions of the 3D printed structures were modified to come up with one that fit into the prototype tested scaled car. The down and drag forces were tested using force sensors. Tests comparisons for the car, with and without the ground effect 3D printed structure, showed 37% increase in the downforce and 26% reduction in the drag force. The capstone was done over 1-semester and was assessed based on progress reports submitted on bi-weekly basis, presentation by the end of the project, final report, and team work participation. Using these assessment tools, many of the ABET outcomes were met as will be shown in the paper.

Introduction

Aerodynamics and flow around car profile are significantly important for F1 design teams. The first designs in the 1950's were relatively sleek, despite having to compensate for the enormous engines mounted in front of the driver. Down force was a little known concept at that time, so the teams tried to rely on eliminating drag to achieve higher top speeds on the long straight runs. At this time, it was not uncommon for tracks to only have 5 or 6 corners, so the teams were able to get by with having very little downforce and skinny tires producing almost zero mechanical grip [1].

The sport progressed rapidly from the 1950's, and smaller and lower to the ground cars were more spread. In the early 1960's, teams began to run tires that were much wider, and the engines were mounted in the rear, behind the driver. These new design features were the beginnings of a decades long race to see who could extract the most grip out of a car, but it wasn't until the late 1960's that teams began attaching rigid wings to the chassis of their cars. The introduction of the wings changed the course of motorsports, and to this day they are the main element that creates downforce in a race car [1]. The principle behind a wing is simple: as air rushes over them, the angle of the wing causes the car to be pushed further into the ground surface, which would allow the tires to retain grip at higher speeds. This continued to dominate sport car industry till late 1990's when carbon fiber manufacturing became cheaper and computer modelling made more intricate designs possible. Formula 1 teams began taking liberties in their designs and started adding more and more wing details [1]. The new designs no longer used wings just to generate downforce, they used them to direct airflow to other parts of their car and into the wake of other cars, as well. Eventually, in just the past few years, this practice has changed where the Formula 1 teams started using the wings to direct the "dirty air" into the front of cars in behind. This has caused the cars to struggle to follow one another, and wheel to wheel racing has become extremely rare [2].

Ground effect aerodynamics is not something that is necessarily new – in the late 1970's Team Lotus first used ground effect airfoils to enormous success. Because the old cars were already extremely dangerous, Formula 1 decided to ban ground effect floors because of a couple of bad incidents in the early 1980's. The early ground effect cars were extremely unpredictable, and after bad accidents the new floors would act like an airplane wing and cause the cars to go airborne. Lack of safety developments in other areas of the car, such as driver head protection and weak suspension, led to the abandonment of ground effect, and since then the cars have relied 100% on wings [3]. However, the development of safety features like carbon monocoques and driver head protection, as well as new technologies like active suspension, make the idea of ground effect seem more reasonable and safer.

Ground effect, while not quite as simple as a wing, is still easy to grasp. Channels are cut into the floor of the car, beginning close to the ground and eventually opening up to the rear of the car. This causes the air flow close to the ground to flow much quicker than at exit, which sucks the car to the ground and enhances downforce. The benefits are obvious: 1) Ground effect floors do not require clean air to generate downforce, 2) they do not produce near as much drag as wings do, 3) they do not generate dirty air like wings do, and 4) cars designed around ground effect typically look much better than cars with an unnecessary amount of wings and protrusions. Formula 1 teams would also be able to spend less money on aero development if they are able to focus only on the floors, allowing some of the smaller teams to compete with the large manufacturers.

This capstone project investigated the effects of ground effect aerodynamic structures on the down and drag forces. The team objective was to improve the efficiency of ground effects by looking into enhancement in the down force.

Methodology

To test the effect of changes in the contour of the car or any other changes, such as ground effects, a testing chamber was needed. A small scale, open loop wind tunnel was built for this purpose. The design was driven by space and cost limitations. The speed inside the testing chamber was designed to simulate a speed of 150 mph in actual racing environment.

Ground effects aerodynamic structures were then design and 3D printed to test the effects on a $\frac{1}{18}$ scaled F1 car. After finalizing the ground effect structures, 241 tests were run for each scenario: with and without the added structures. Each test was run for a total of 1 minute. The drag and down forces were measured. The average of each category was compared to the other.

Experimental Setup

Wind Tunnel Setup

An open loop wind tunnel was used for testing purposes due to space limitations and to keep the cost of the project low. The dimensions of the built up wind tunnel are shown in Figure 1. Figure 2 shows the actual built wind tunnel. A 3000 cfm (cubic feet per minute) (1416 lit/s) fan was installed at the inlet of the diffuser having a 20 × 20 sq.in area (37.16 m^2). The converging section supplied the air into 6 × 6 sq.in (3.34 m^2) testing section. Thus, based on ASHRAE guidelines for fans with ducts, the contraction flow coefficient inside the 48 inch converging section would be approximately C_c=0.25 [4].

Therefore, if Q_{fan}=3000 cfm, then the actual flow could be estimated using equation (1). The velocity in the testing section was then estimated using equation (2), as shown.

$$Q_{act} = Q_{fan} \times C_c = 750 \text{ cfm } (354 \text{ lit/s}) \qquad (1)$$

$$V = Q / A = 750 / 0.25 = 3000 \text{ fpm} = 34 \text{ mph} \qquad (2)$$

The scaled F1 car was $\frac{1}{18}$ compared to full size F1-car. Thus, assuming the dynamic viscosity for air in the wind tunnel was the same as in real race and equating the Reynolds number gave the needed velocity of air inside the testing section as shown in equation (3), where V_m is the model car velocity, V_{car} is the actual car velocity, and ρ is the density. With a model air velocity of 34 mph inside the testing section, using a volume ratio for car-to-model of 18:1 and if density of air at 20 C is 1.2 kg/m^3 then when using the ideal gas law, the velocity of the actual car would range between 150-160 mph.

$$V_m = V_{car}\,\frac{\rho}{\rho_m}\,\sqrt[3]{\frac{volume_{car}}{volume_m}} \tag{3}$$

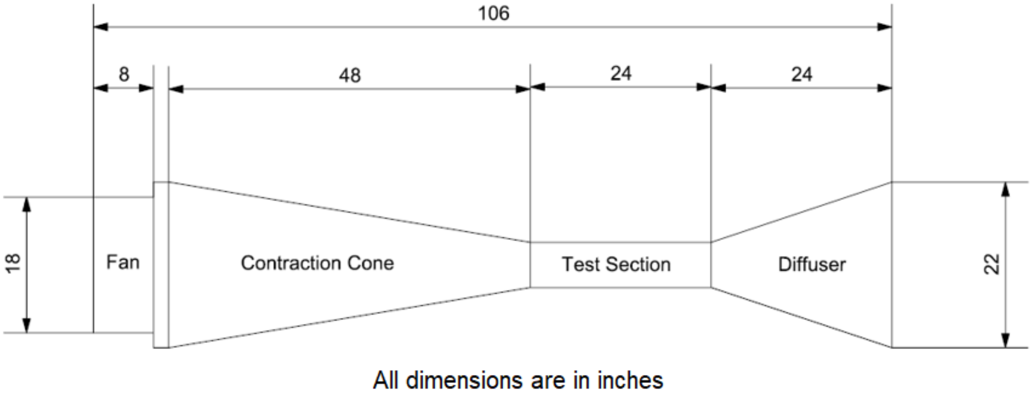


Figure 1. Conceptual design for the testing wind tunnel

Figure 2. Finalized built-up wind tunnel

Ground Effect Structure Design and Fabrication

The design of the ground effect structure needed to provide 1) an increase in down force with no change or increase in the drag force or 2) a reduction in the drag force with no change or reduction in the down force. To achieve that, the structure was designed with venture gates, running from around the center of the car and opening up to the rear of the car. Two side skirts were also needed to trap air inside the venture gates. These side skirts needed to run as close to the ground as possible. Finally, a skid-plate, running almost over the length of the floor, was designed as close to the ground as possible and opened up to meet the Venture gates at the back. Five different revisions were designed and installed after being 3D printed. The designs are shown in Figure 3 for revisions A through E. The final adopted revision “Revision F” had to

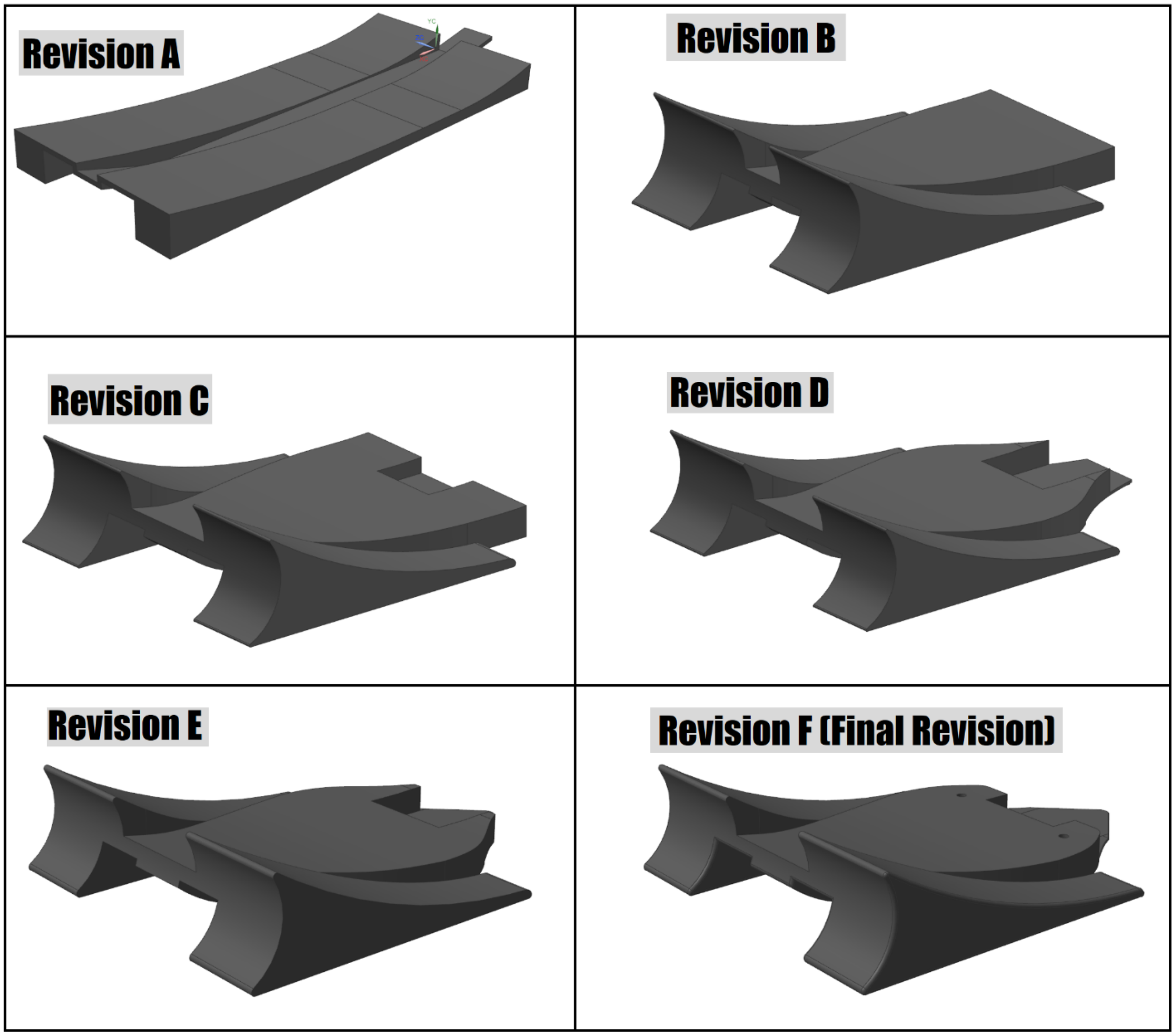


Figure 3. Ground effect structure revisions and the final revision

include holes to secure the structure to the car by using screws in-addition to smoothing the edges of the previous revisions. Figure 4 shows side and isometric views of the final revision.

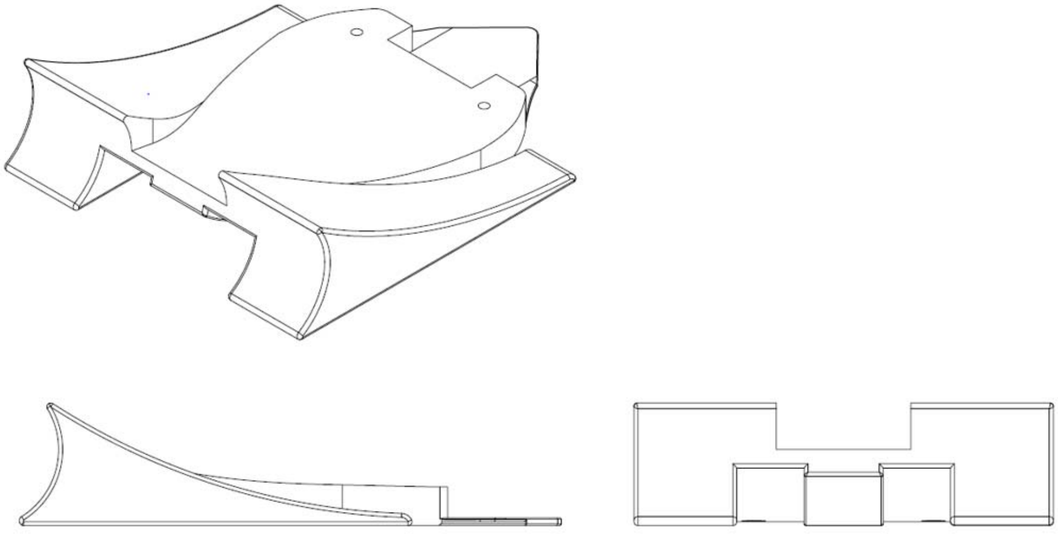
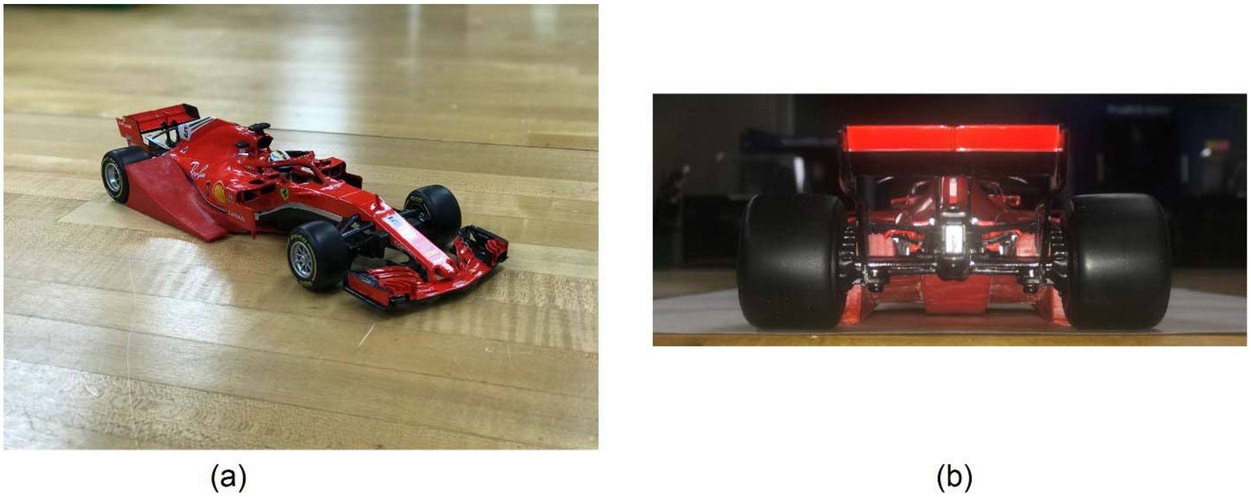


Figure 4. Isometric views of the final ground effect structure

Testing of the Ground Effect Structures

After finalizing the ground effect structure, the model was sanded and covered in acetone to give it a smooth surface finish. Figure 5 shows the final product installed on the model car. Two force sensors (Brand: Vernier; model: GDX-FOR) were used to measure the down and drag forces with and without installing the 3D printed ground effect structures. The sensors had ±0.01 N accuracy and can measure forces in the range of 0.1–50 N. One sensor was placed in the diffuser behind the car to measures changes in the drag force and the other one was placed under the car to measure changes in the down force. Both sensors are shown in Figure 6. The force sensors came with its own data logging software which allows storing the data which facilitates data sorting and analysis. Figure 7 shows an example of the data being plugged into a laptop while the car under testing.


(a)

(b)

Figure 5. Final revision of the 3D printed ground effect structure painted and installed on the scaled F1 car (a) side view and (b) rear view

Figure 6. Model car tested inside the testing chamber with force sensors being installed underneath the car and behind it to measure the down and drag forces respectively

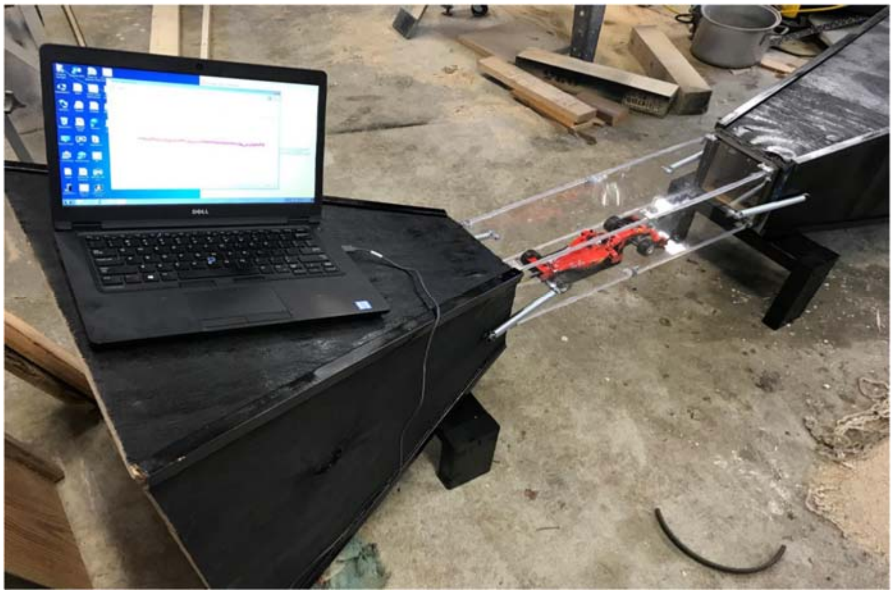
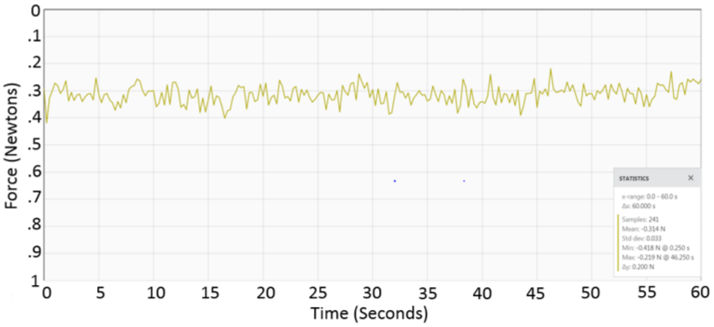
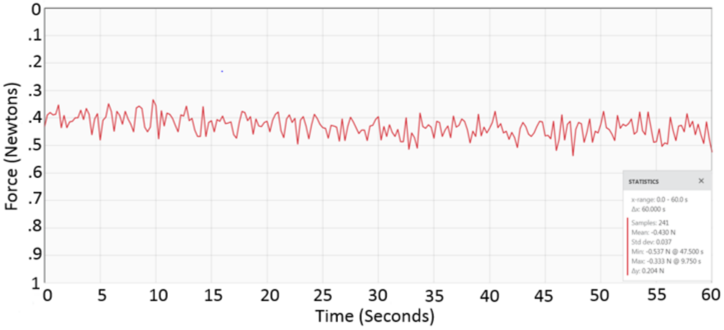


Figure 7. Forces being recorded and saved into the laptop

A total of 241 tests were conducted for each case. Samples of the recorded data for the down and drag forces with and without the ground effect structure are shown in Figures 8 and 9, respectively. Based on the samples shown in Figure 8 and Figure 9, it was seen that the drag force was reduced whereas the down force was increased. Averages of all tests were calculated along with statistical analysis as shown in the next section.

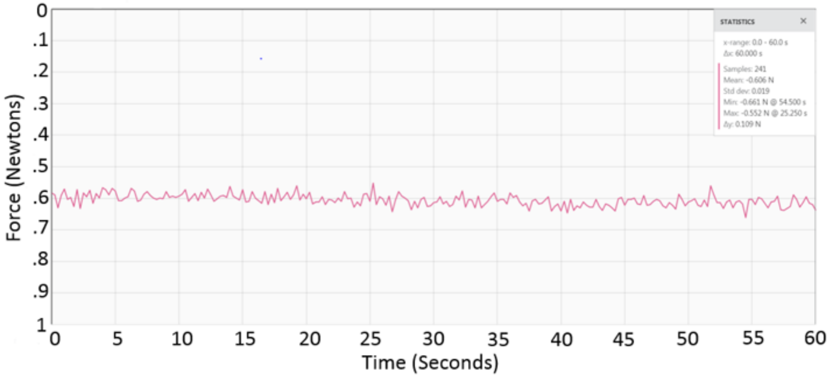


(a) Down foce with no ground effect structure

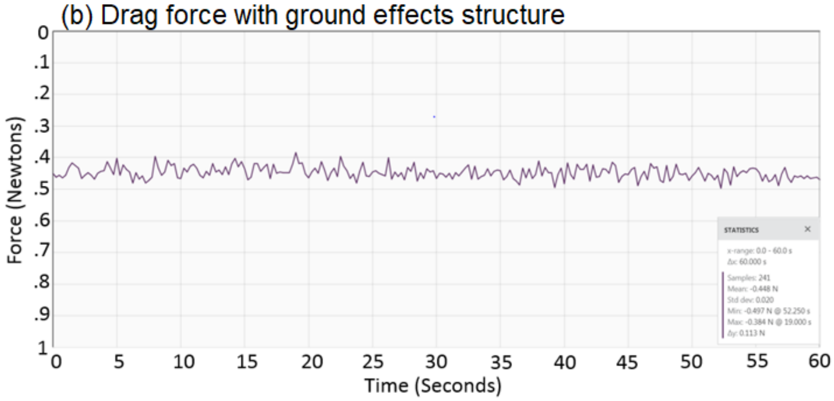


(b) Down force with ground effects structure

Figure 8. Down force measured on the scaled F1 car (a) without and (b) with the ground effects structure installed



(a) Drag force with no ground effects structure



(b) Drag force with ground effects structure

Figure 9. Drag force measured on the scaled F1 car (a) without and (b) with the ground effect structure installed

Analysis

The averages and standard deviation for the down and drag force samples are shown in Tables 1 and 2, respectively. With the ground effect structure installed, the down force was increased by 36.9% and the drag force was reduced by 26.1% compared to the stock model having no ground effect structure installed. The random uncertainty "u_r" of the samples along with 95% confidence level were estimated using equation 4.

$$u_r = \frac{t_{95\%}\left(\frac{S.D.}{\sqrt{n}}\right)}{\bar{F}} \times 100 \qquad (4)$$

where $\bar{F}$ is the average force of the samples, $t_{95\%}$ is the confidence interval coefficient at 95% confidence level and has a value of 1.96, S.D. is the standard deviation of the collected samples and n is the number of samples. The top part of the equation (4) represents the standard error in the samples collected $\left(S.E. = t_{95\%}\frac{S.D.}{\sqrt{n}}\right)$.

The accuracy of the force sensors used added another uncertainty which could be treated as the bias uncertainty "u_b". The accuracy of the sensor was ±0.01 N, thus "u_b" was estimated as shown in equation (5). Finally, the combined uncertainty "u_t" could be estimated by adding the random and bias uncertainties together as shown in equation (6). The random, bias, and relative uncertainties for the stock and modified model are shown in Table 1 and Table 2 for the down and drag forces, respectively. The random uncertainty for the down force was higher than that for the drag force measurements. The bias uncertainty was almost 2-4 times the random uncertainty which shows the importance of including this part in the final uncertainty level. Based on the total uncertainty, the drag force measurements were less variant than those collected for the down force, but all results were less than ±4% which was acceptable.

$$u_b = \frac{0.01}{\bar{F}} \times 100 \tag{5}$$

$$u_t = \sqrt{{u_r}^2 + {u_b}^2} \tag{6}$$

Table 1. Statistical comparison for the down force with and without ground effects

Down force Analysis		
	No ground effects	**With Ground Effects**
n	241	241
$\bar{F}$ (N)	0.314	0.43
S.D.	0.033	0.037
$t_{95\%}$	1.96	1.96
S.E.	0.00417	0.00467
u_r	**1.33%**	**1.09%**
u_b	**3.18%**	**2.33%**
u_t	**3.45%**	**2.57%**

Table 2. Statistical comparison for the drag force with and without ground effects

Drag force Analysis		
	No ground effects	**With Ground Effects**
n	241	241
$\bar{F}$ (N)	0.606	0.448
S.D.	0.019	0.02
$t_{95\%}$	1.96	1.96
S.E.	0.00240	0.00253
u_r	**0.40%**	**0.56%**
u_b	**1.65%**	**2.23%**
u_t	**1.70%**	**2.30%**

Down force and drag force could be translated into actual car using the following dimensionless group $\left(\frac{F}{\rho V^2 L^2}\right)$ where F is the force and L is the characteristic length in this case is $\sqrt[3]{volume}$. Equating this non-dimensional group between the real and model car, gives a form for the actual forces on a full scale F1 car as shown in equation 7. The volume ratio is the actual to model car ratio and is equal to 18.

$$F = F_m \left(\frac{\rho}{\rho_m}\right)\left(\frac{V}{V_m}\right)^2 (volume\ ratio)^{2/3} \tag{7}$$

Project assessment

By the end of this project, the students tested ground aerodynamic effects on a scaled F1 car inside a wind tunnel that was built by the students. Through the continuous submission of biweekly progress reports, presentation, and final reports, the students met many of the ABET old outcomes such as (3.1) An ability to apply knowledge, techniques, skills and modern tools of mathematics, science, engineering, and technology to solve broadly-defined engineering problems, (3.3) improving written and oral communication skills (3.4) conducting tests, measurements, calibration and improving processes, and (3.5) demonstrating team work skills. The final capstone course grade was based on the elements shown in Figure 10. Performance assessment and feedback were done through the evaluation of biweekly submitted reports by the students. There were four main categories toward the final score: biweekly reports, final report, presentation, and team work evaluation. Table 3 shows assessment methods that reflected the ABET outcomes mapping with the project assessment tools followed.

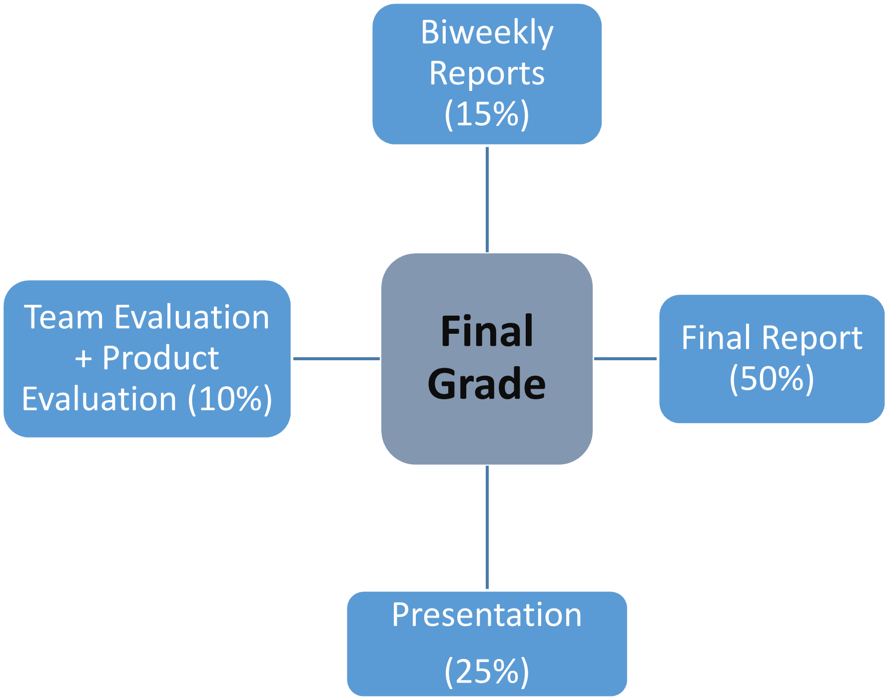


Figure 10. Capstone assessment structure

Table 3. ABET students learning outcomes and assessment methods used

ABET ETAC Outcomes		Assessment Methods
3.1	An ability to apply knowledge, techniques, skills and modern tools of mathematics, science, engineering, and technology to solve broadly-defined engineering problems	Project proposal, final Report and biweekly reports
3.3	Improving written and oral communication skills	Presentation and biweekly reports
3.4	Conduct tests, measurements, calibration and improve processes	Biweekly reports, draft report, and final report
3.5	Team Work	Self evaluation and oral assessment by the instructor

Conclusions

In this capstone project, the students designed and built a wind tunnel which was used to test ground effect aerodynamics on a scaled F1 car. The team designed and modified different version for the ground effect structures which were printed using 3D printers. The final version was screwed to the bottom of the car and tested inside the built wind tunnel. The down and drag forces were tested inside the wind tunnel for the scaled car as was in stock and as modified after adding the ground effect structure. The testing showed that there was approximately 37% increase in the down force while reducing the drag force by approximately 26%. Relative uncertainty, including random and bias uncertainties, was less than 4% for all tests.

The students covered various topics that they learned through their program and beyond. The aerodynamics, drag and lift analysis are usually barely covered in fluid mechanics and other courses within the program of mechanical engineering technology. The students had the opportunity to widen their knowledge in addition to increasing their experimental and measurement skills. The project also helped the students meet many of the ABET outcomes as was shown in Table 3.

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