Numerical Simulation of the Aerodynamic Drag of a Dimpled Car

By: Ross Neal

Abstract:

The drag coefficient of a dimpled half-car of various dimple radii and densities and a half-car without dimples was calculated using a numerical fluids solver (CFX). The dimples were created using spherical cut-outs along flat surfaces in a grid pattern with a set ratio of the density of dimples and the dimple radii. The half-cars were meshed using both body sizing and inflation layer methods. The numerical solver simulated the half-car as a full car by a symmetry boundary condition to save computing time. The solver calculated the drag force over the front face of the car using air at $25^{o}C$ at 25 m/s. The various design points of differently sized radii dimples drag force was calculated in a parameter study and the data points are graphed and fitted to an equation. The drag coefficient was calculated manually using the drag force data points.

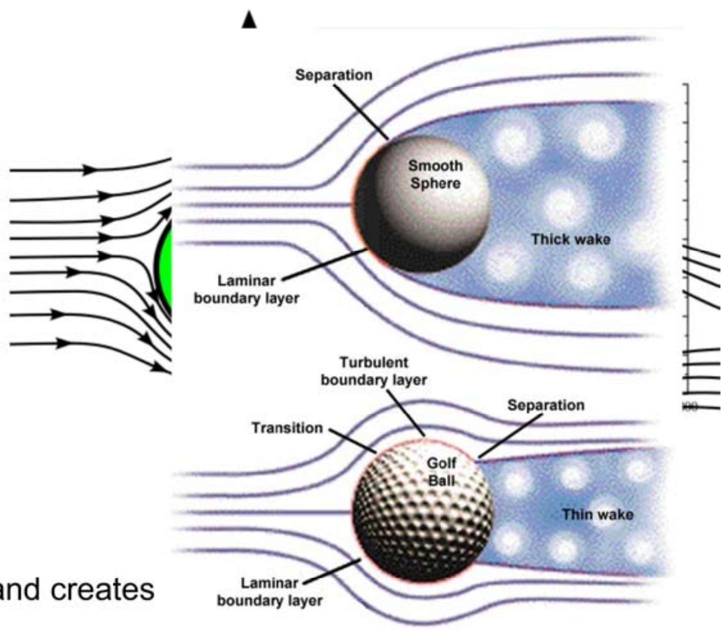
Introduction:

Ever since gasoline prices have risen and smog/emissions from cars has become more of a serious problem for the environment, consumers have been more conscious about the environment and their wallet when it comes to purchasing cars. Specifically, consumers want the ideal car that has no emissions or high gas mileage while maintaining a decently sized interior cabin. Car manufacturers have been plagued with this problem, especially the past few years, since consumers have stopped buying bulky sports utility vehicles and started buying more environment friendly and sub-compact cars.

To appeal to consumer demand as well to abide by state laws to offset carbon emissions, car manufacturers started selling no-emission electric cars. While electric cars may seem like the perfect solution, they have an Achilles heel: electric cars have a limited range and cannot be recharged quickly. Most electric cars have a range under 90 miles except for a few very expensive cars. Electric cars have a limited range for two reasons: current battery technology (Lithium-ion) is more expensive (in the short term) and are 18 times less energy dense as gasoline, making electric cars heavier and reducing range. Furthermore, electric cars currently cannot charge as quickly as refueling a conventional combustion engine car: charging electric cars can take anywhere from 2 to 8 hours to fully charge depending on the charger or voltage of the power source. To combat the electric car's short range, car manufacturers have made electric cars smaller, reduced their weight, and decreased their aerodynamic drag. Similarly, car manufacturers have implemented the same strategy with sub-compact cars to increase their mileage; however, small and very aerodynamic cars are not

comfortable to ride in (as seen in Figure 1). Nevertheless, there is a way to decrease aerodynamic drag without sacrificing cabin space through dimpling the surface area of the car.

The first practical use of a dimpled surface came from the shape of a golf ball. Dimpled Golf balls have a different flight impetus trajectory (as shown in Figure 2) rather than a slightly skewed parabolic trajectory to allow the ball to travel further before hitting the ground. This discovery came as an accident as roughened golf balls traveled further than smooth ones in the early days of golf. The reason dimpled balls travel further is due to Magnus force lifting the ball (shown in Figure 3) as well as dimples reducing drag in the flight direction of the ball. The Magnus force effect results from the ratio of air drag on top of the ball versus the bottom of the ball. When the ball has backspin, the top of the ball moves slower relative to the air over it and has less drag. At the same time, the bottom of the ball moves faster relative to the air underneath it and creates more drag. Since the air on top of the ball is moving faster due to less drag, there is less pressure on top of the ball due to the Bernoulli principle. This principle also applies to the increased pressure on the bottom of the ball. The low pressure on top and high pressure on the bottom of the ball gives the ball lift. The other effect of dimpling a ball (or any other relatively streamlined body), is that the dimples increase surface drag by creating a turbulent boundary layer on the surface of the ball. Turbulent boundary layers more easily follow the contours of a ball reducing the size of the wake or boundary layer separation behind the ball compared to laminar flow over the surface of a ball, which has a large wake or boundary layer separation as shown in Figure 4. The wake behind the ball creates a drag force opposite to the flight path due to the lower pressure of the wake behind the ball versus the higher pressure in front of the ball.



This dimpling effect may be used not only for golf balls, but for streamlined vehicles as well. In fact, dimpled vehicles have already been tested in the famous television show called Mythbusters. In one Mythbusters episode, the mileage of the car

was tested through dimpling a sedan ca

carving dimples from it (shown in Figure

types of configurations of the clay on the

outer surface of the car, the surface of t

was put inside the car to preserve weigh

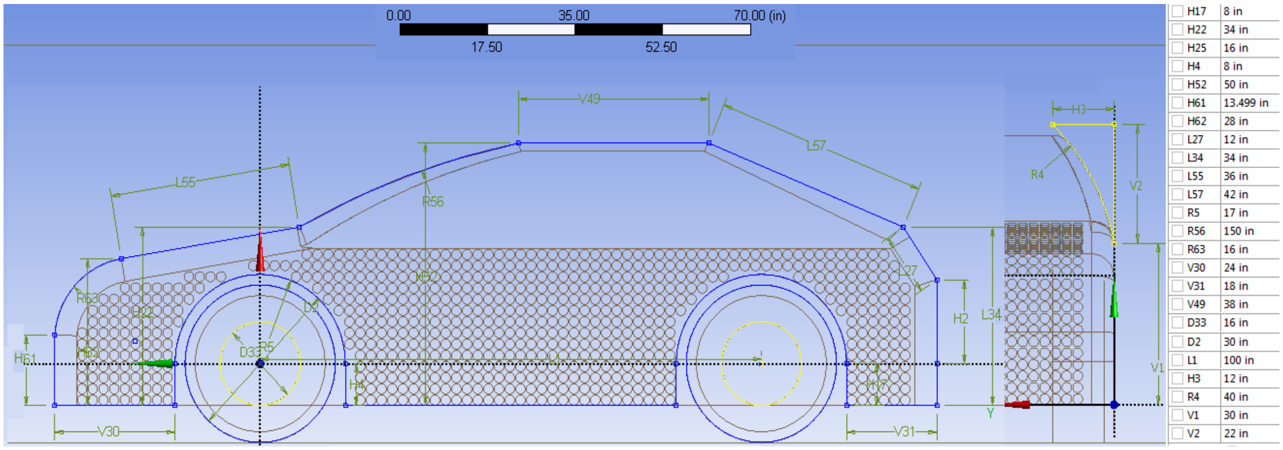
surface and was put inside the car. Each configuration was driven 5 times down a track at a constant 65 mph and the results were averaged. Calculated results indicated that the smooth clay car and the car with all the clay inside got 26 mpg mileage whereas the dimpled car got 29.65 mpg mileage (a significant 12% increase). Also, the effect seems to be scalable as well. Brian Vaughn, a Mythbuster fan, did a similar experiment with Hot Wheels cars and found that the dimpled car won more races compared to the normal smooth car by a significant margin of 4 to 1 (cars shown in Figure 6). There is a even a company called SkinzWraps that can dimple any car that makes a micro-dimpled wrap (shown in Figure 7) that can be applied to a car to increase gas mileage. They claim up to 20% increase in mileage depending on shape/weight of the car. Unfortunately, no independent testing results could be found to verify those claims.

To validate claims that dimpled cars have less drag, I decided to numerically model and test to see if dimples really do reduce drag. Since dimples on a car decreased drag on the car from different dimple densities experimentally as explained before, I tested to see how the drag force in the front of the car would be affected by increasing/decreasing the density/size of the dimples. My goal was to prove that dimples can reduce drag and therefore increase mileage so that cars can pollute less and so that consumers can save money at the gas pump.

Modeling:

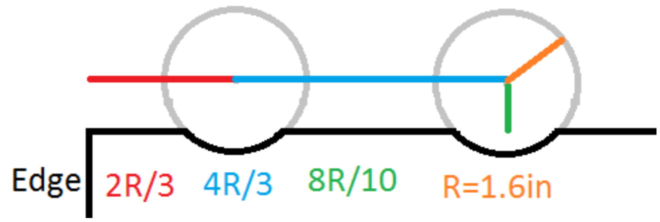
I simulated a sphere-dimple shape because it was relatively easy to model and it has already proven shape that reduces drag by increasing surface drag and decreasing wake experimentally (a separate simulation experiment would have to be conducted to test if other shapes are be more efficient at creating surface drag). I simulated the car itself with dimples instead of a dimpled plate because I wanted a numerical value for the drag force in the front of the car in order to calculate the drag coefficient of the car. I modeled half of a car because I could decrease computer simulation time because the airflow over the car should be about symmetrical at a high enough wind velocities (high Reynolds numbers) down the symmetrical axis of the car.

I started modeling (using ANSYS) a rough outline of a sedan car (no side mirrors for simplicity) with an outline of lines and arcs with the following measurements and cut out a wedge of the side (shown in Figure 8). The body of the car was extruded 38 inches (half the width) and the wheels were extruded 12 inches (the wheel well was

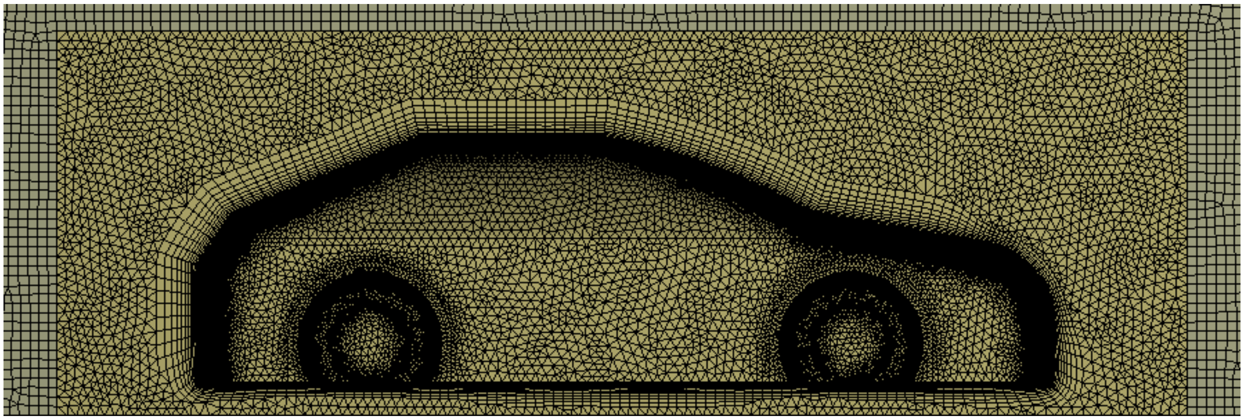


filled in behind the tires). The top edges of the car were rounded with a 4.4 inch radius and the front of the tire was rounded with a 2 inch radius.

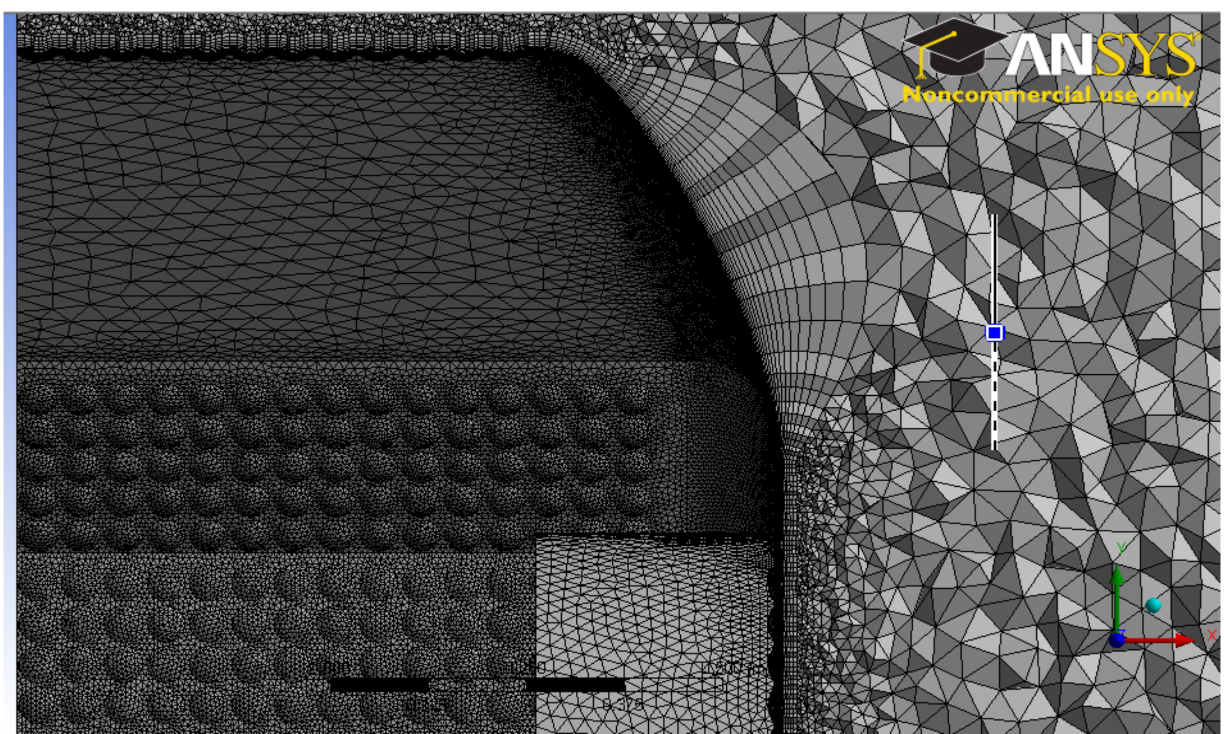
All the flat planes of the car (including the underside) were dimpled with partial spherical cut-outs in a standard grid with the following measurements (seen in Figure 9) in one dimension. The measurements were made in terms of the radius variable so that I could test different dimple densities and sizes as a factor of the sphere radius. Then, the car was enclosed in a 235”x60”x80” (LWH) rectangular prism and was used to create a cavity in the prism with wheels touching the bottom and placing it 70”x23” (LW) from the front left of the car. Then the prism was encapsulated in another rectangular prism with the following padding: 100” (front), 250” (back), 60” (side),45” (top), .00005” (bottom) 0” (symmetry side) making the overall dimensions: 585”x98”x107” (LWH). The outer encapsulating box should have be larger to be able to include all air eddies formed around the surface of the car, but there was a deadline and limited simulation time.

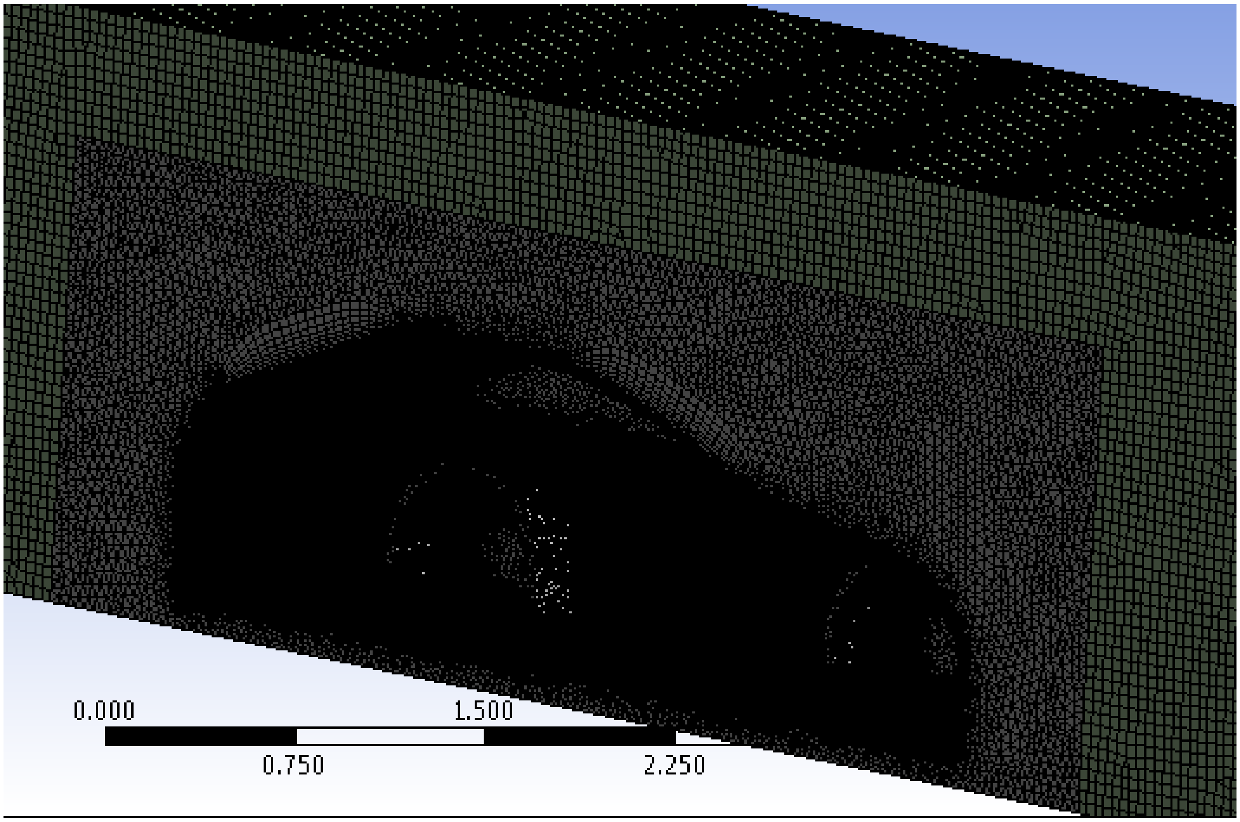


The outer box was meshed with a body sizing method of .05 meters and a multi-zone method with hexa/prism shapes and free mesh tetrahedrons. The smaller box was meshed with a body sizing method with .05 meters with 3-degree normal follow on arcs with an 20 inflation layers at a 1.2 growth rate (20% increase). There was not enough

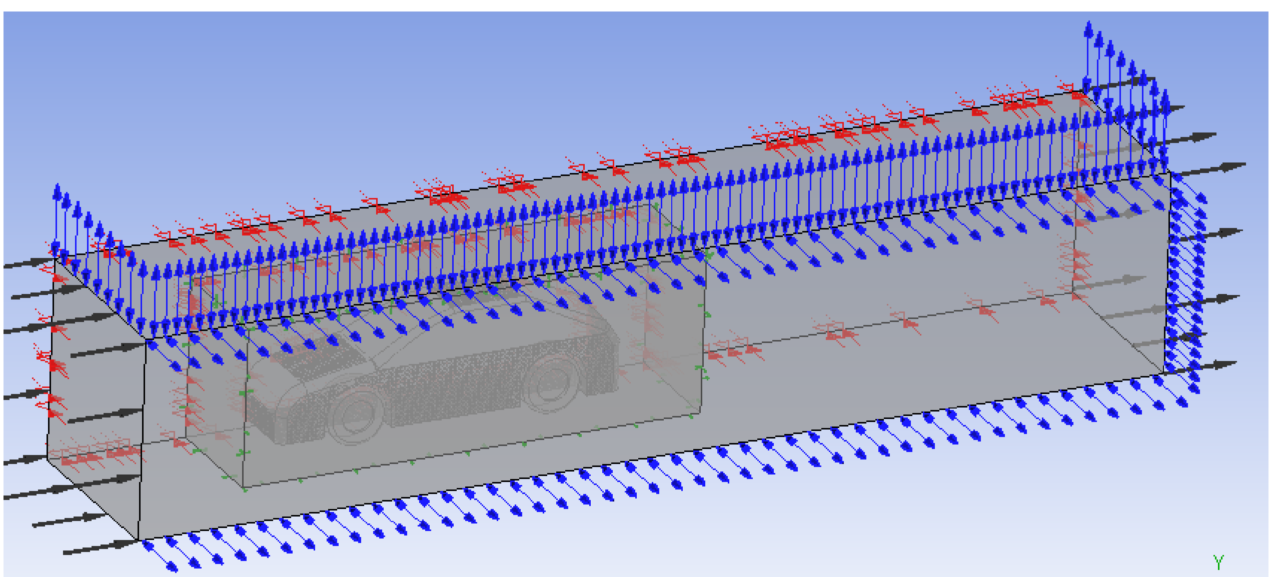


time to do a proper mesh independence study since the meshing methods created 19.5 million elements and 6.8 million nodes which took over two days to solve. A few of the meshes of the cars are shown below in Figures 10-12 for comparison and to show the effect of meshing methods.

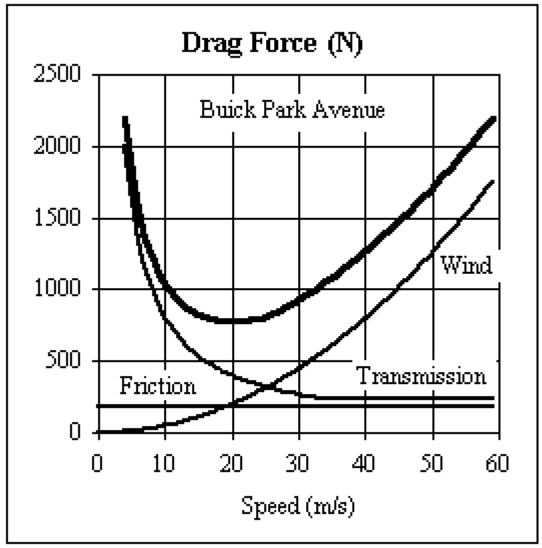




A fluid numerical solver (CFX) was used to calculate the drag force. The boundary conditions were placed on each of the sides of the rectangular prisms shown below in Figure 13.



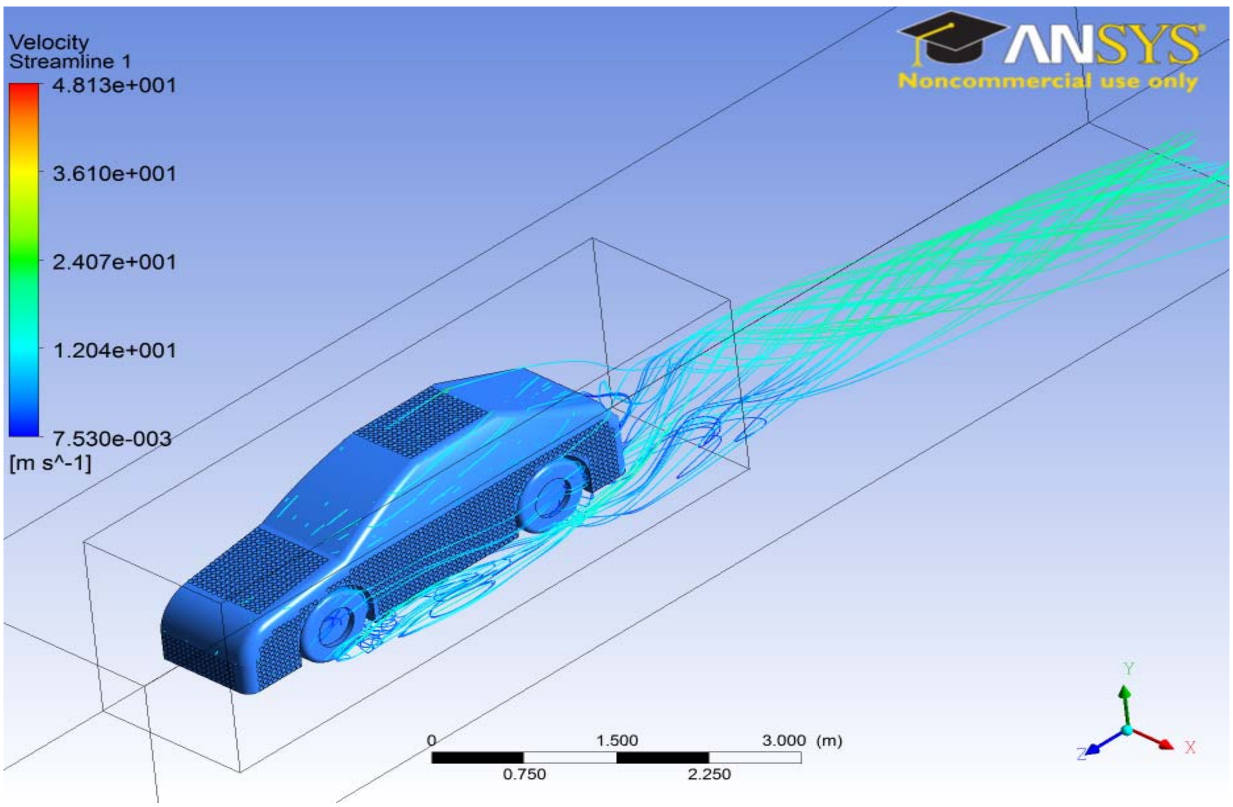
The symmetry boundary (red) makes it so fluid flow is symmetric over the plane to simulate other half of the car. The blue arrows show open boundaries where air can flow in/out. The outlet boundary condition (right black arrows) has 0 kPa pressure where the inlet wind can only leave. The inlet boundary condition (left black arrows) was set at a wind speed of 25 m/s air at 25^{o}C, 5% intensity, and a density of 1.185 kg/m^3 to simulate car driving at approximate highways speeds (about 60 mph) where the drag force of most cars is at a minimum shown in Figure 14[1]. The boundary condition for the ground floor was modeled as a no-slip wall without roughness. Ideally, the floor should be modeled with shearing forces as well as roughness for more accuracy. Again, in the interest of reducing computation time, the ground was made slipperly which will artificially decrease the drag force results on the car because the air underneath the car would cause more drag to the car due to airflow friction between a dimpled bottom of the car and the rough road.



Two separate simulations were completed: a parameter study of a dimpled car with a dimpled sphere radius of 1, 1.3, 1.6, and 2 inches and a single simulation of the car without any dimples. Both simulations ended with more than a .0001 variance but reached a relative steady state which indicated there is a unsteadiness at some of the boundaries due to air eddies intersecting those boundaries. Also, there was a

1 http://usna.edu/Users/physics/schneide/Buick.htm

unsteadiness at the outlet boundary because the numerical solver I used has to put in one-way walls at 4% of the boundary to prevent air backflow due to air eddy currents at that boundary. Both of these issues affected my final drag force results slightly but could be remedied by making the bigger encapsulating box larger to incorporate all air eddy currents (shown on Figure 15).



Results:

The results of my simulations showed were quite surprising: the dimpled car did decrease and also increase the drag force (in the direction of travel for the car) slightly compared to the smooth car. Since the drag force is directly correlated to the From the drag force, the drag force coefficient can also be calculated using the calculated front cross-sectional area of the car (3.08154 m^2), the density of the air at 25°C (1.185 kg/m^3), and velocity of the air (25 m/s) using the following equation for the drag force coefficient: . The drag forces as well as the drag coefficients are shown in the table below in Firgure 16.

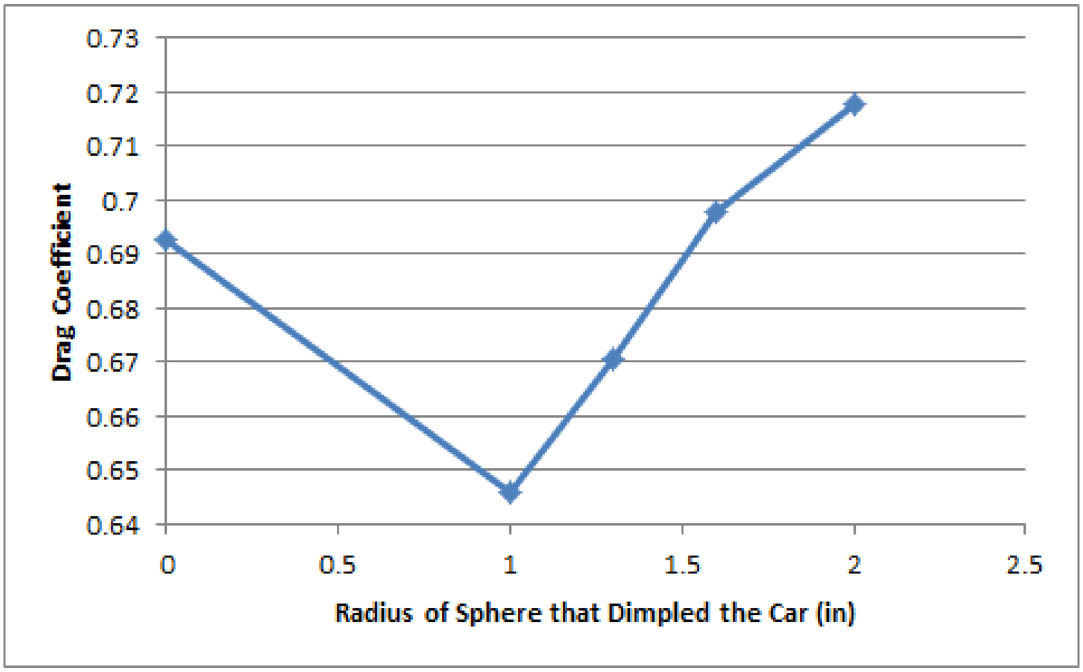
Radius of Sphere that Dimpled the Car (in)	Drag Force in Front of Car (N)	Drag Coefficient	Drag Coefficient Difference Compared to Smooth Car	Drag Coefficient % Difference Compared to Smooth Car
0 (no dimples)	790.28	0.69254	0	0
1	736.88	0.645744	-0.0468	6.7571
1.3	765.34	0.670684	-0.02186	3.1558
1.6	796.26	0.69778	0.00524	-0.757
2	818.98	.71769	0.02515	-3.632

According to the results, the larger and less dense dimples actually hinders the car and creates more drag than the smooth car of about .76-3.6% whereas the smaller and more frequent dimples did actually decrease the drag coefficient by almost 7%. Interestingly, the 1.3 inch dimples and the 2 inch dimples decrease and increase the drag coefficient respectively by about the same 3%.

Figure 16: Table of design points correlating radius of dimples (increasing dimple size decreases amount of dimples on car) and drag force/coefficient in the front of the car.

The graph of the data below on next page (Figure 17) shows that there is a positive linear correlation between radius of the sphere dimples and the drag coefficient (minus the smooth car). In fact, since the correlation between the drag coefficient and the radii of the sphere dimples was so linear, I entered the data (minus the smooth car) in a linear regression calculator to find the equation of the slope of the correlation:

.



Conclusion:

Given more time, I would test even more data points below 1 inch diameter spheres in the parameter study to test the limit of dimpling a car that still reduces the drag force on the car. I would have like to have seen how the results would have been affected with proper setup and increased computing time discussed earlier: refined mesh (by doing a mesh independent study), bigger boundaries, and coarse road.

In conclusion, a positive correlation was found between the dimple radii on the surface of the car and the calculated drag coefficient and a linear equation was calculated from that positive correlation. The results also demonstrated that dimples too big or less dense actually increase the drag on the car so dimples do not always decrease fuel economy. The geometry, size, and density greatly affect the drag and mileage of a car for better or worse.