Using Race Car Aerodynamics to Teach Mechanical Engineering Students About Fluid Mechanics

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Abstract

The study of racecar aerodynamics provides an interesting application for illustrating principles of fluid mechanics. Racecars are aerodynamically designed to minimize drag force and maximize downforce (unlike airplanes which are designed to minimize drag and maximize lift). Drag forces limit maximum speed and affect fuel consumption while downforce is used to provide stability when driving around corners. Racecars use various “appendages” and body contouring to provide downforce and decrease drag force. This paper describes a 2-3 week wind tunnel lab exercise designed to study the aerodynamics of racecars. The lab is used in a junior level introductory fluid mechanics course to teach mechanical engineering students about the principles of lift and drag and the relationship between pressure and velocity as described by Bernoulli’s equation. We use several types of model racecars and students measure the lift (downforce) and drag as a function of velocity. In addition the students measure the pressure distribution on the surface of the model racecars and use Particle Image Velocimetry (PIV) to quantitatively measure the flow field around the car that contributes to the lift, drag and pressure measurements. By comparing the data from different car types students learn about lift and drag. This paper describes the experiments, explains how to instrument the cars, and presents a set of typical results for five different model car types.

Introduction

An automobile is one of the most basic mechanical engineering systems. Cars, and in particular racecars, are one of the things that attract students to the study of mechanical engineering, and the study of automobiles has entered the undergraduate mechanical engineering curriculum in a variety of ways. Many schools participate in the SAE sponsored Mini Baja or Formula Competitions which are seen as an effective way to motivate students to learn (see for instance Rencis, 1999 or Morris and Fry, 2001). Another example is a program at the University of South Carolina which uses an instrumented Legends-class race car in a capstone mechanical engineering course to teach students to develop a systems approach to problem solving (Lyons and Young, 2001; and Lyons, Morehouse and Young, 1999). Several schools such as the Milwaukee School of Engineering (Musto and Howard, 2001; Musto, Howard and Rather, 2000), and the University of Arizona (Umashankar et al, 2001) report using racecar design in outreach programs to high school students. In addition a number of schools now offer motor sports programs as part of a Mechanical Engineering curriculum.

At Union College we have developed a racecar aerodynamics laboratory exercise that is used in a junior year fluid mechanics course to teach students about the relationship between pressure and...
velocity as described by Bernoulli’s equation and about the role of lift and drag in vehicle design. The objective of this paper is to describe that laboratory exercise and present some typical results. The following section presents background material on racecar aerodynamics. This is followed by a section describing the instrumentation of the model racecars and the test equipment used in the experiments. Then we outline the test procedure which consists of (1) surface pressure measurement (2) PIV flow field analysis and (3) Lift and Drag Measurements and present and discuss some typical results.

**Race Car Aerodynamics**

In the highly competitive world of modern automobile racing the difference between winning and losing can be measured in fractions of a second. One of the major factors that racecar manufacturers focus on to decrease lap times and gain a competitive edge is the aerodynamic performance of the vehicle. The lift and drag forces that act on a race vehicle impact its performance. The body shape of each car is formed in an attempt to control these forces to achieve balance in handling, maximum downforce, and minimum drag. Figure 1 shows a schematic of a racecar and the flow field around it.

Drag is the force imposed by the air that acts opposite to the path of the vehicle’s motion. Drag is detrimental to vehicle performance because it limits the top speed of a vehicle and increases the fuel consumption, both of which are negative consequences for race vehicles. Low drag vehicles usually have one or some combination of the following characteristics: streamlined shape, low frontal area, and minimal openings in the bodywork for windows or cooling ducts. The drag performance of vehicles is characterized by the drag coefficient \( C_D \) which is defined as:

\[
C_D = \frac{F_D}{\frac{1}{2} r V^2 A}
\]  

(1)

Where \( F_D \) is the drag force, \( r \) is the air density, \( V \) is the free stream velocity, and \( A \) is the frontal area of the vehicle. This non-dimensional coefficient allows the drag performance between different vehicles and different setups of the same vehicle to be compared directly.

Lift is the other of the two main aerodynamic forces imposed on a race vehicle, but unlike drag, lift can be manipulated to enhance the performance of a racecar and decrease lap times. Lift is the force that acts on a vehicle normal to the free stream velocity. As its definition implies, lift usually has the effect of “pulling” the vehicle towards the atmosphere and away from the surface it drives on. However, by manipulating the racecar geometry it is possible to create negative lift, or downforce. Downforce enhances vehicle performance by increasing the normal load on the tires. This increases the potential cornering force which allows the vehicle to corner faster and reduce lap times. The lift of the vehicle is characterized by the lift coefficient \( C_L \) and is defined as:

\[
C_L = \frac{F_L}{\frac{1}{2} r V^2 A}
\]  

(2)

Where \( F_L \) is the lift force, \( A \) is the area of the upper surface of the vehicle, and the other variables are as defined above. Like the drag coefficient, the lift coefficient is non-dimensional to allow
for direct comparison, but unlike the drag coefficient, the lift coefficient can have a negative value which means that a vehicle is experiencing downforce.

The lift and drag forces are the two components that contribute to the net pressure force acting on the vehicle’s surface. The pressure over the vehicle varies across the surface and is dependent on the geometry of the vehicle. The pressure on the vehicle acts normal to the surface and contributes to the lift and drag forces accordingly. The pressure at each point on the surface of the vehicle can be characterized by the pressure coefficient \( C_P \) which is defined as:

\[
C_P = \frac{p - p_8}{\frac{1}{2} \rho r V^2}
\]  

(3)

where \( p \) is the static pressure at the vehicle surface, \( p_8 \) is the free-stream static pressure, and the other variables are as defined above. The value of \( C_P \) is one at a stagnation point and is zero when the local and free-stream pressures are the same such as over flat sections of the vehicle (implying equal velocities so long as Bernoulli’s equation is applicable). A negative pressure coefficient occurs when the local pressure is smaller than the free stream pressure implying that the local velocities are greater than the free stream velocity (so long as Bernoulli’s equation applies). For further information on race car aerodynamics the reader is referred to Katz (1995), Smits (2000), Schenkel (1977), Katz and Dykstra, (1992) or Duncan, (1994).

**Radio Control Models**

The vehicles used for the experiments are 1/12 scale radio controlled cars. Radio controlled cars are raced on most any surface from dirt off-road circuits to paved oval tracks, and there are many types of cars to suit the particular task. The bodies of radio controlled vehicles are molded from Lexan and are modeled after full scale versions of race and road vehicles. They are suitable models to explore racecar aerodynamics, although it is important to point out that the results of the tests done on the 1/12 model are not scalable to full size racecars because we can not operate our wind tunnel at 12 times typical race car speeds! (The data would scale up to full size vehicles traveling at roughly 5 mph)

We studied 5 different car types which required two different chassis types on which to mount the bodies. The chassis were made by Associated Electrics (models RC12L3 and RC12L3O). The bodies chosen were a Ford Taurus NASCAR racer, a 1969 Dodge Charger similar to the General Lee in the Dukes of Hazard television show from the 1980s, a baja Beetle which is a normal VW Beetle that is modified for driving off-road, a Nissan P-35 closed-top LeMans prototype racer, and a generic hatchback similar to a Mini Cooper. The NASCAR car was made by Protoform, the Dodge Charger was made by Bolink, and the other two were made by Dahn’s. These body types are all quite different and were chosen in an effort to explore a wide range of flow situations. Pictures of the five body types can be seen in Figure 2. (Note: We did not test the NASCAR, hatchback or Beetle with the spoilers shown in the pictures.)

**Model Instrumentation**

The model racecars are purchased in kit form, and they have to be assembled and instrumented prior to testing. First the chassis needs to be assembled. The manufacturer’s instructions make
this a simple process, but it should be noted that the kits include all the bits necessary to construct a functional vehicle, and for this experiment the chassis needs only carry the body. Thus, some of the instructions can be modified for the sake of simplicity. For example, we replaced the shock absorbers with straight linkages. The step is to mount the car bodies. All of the bodies used in this experiment come molded with borders that outline the vehicle geometry. We used these guidelines to mount the bodies such that they were centered on the chassis, level with the main chassis plate, and at the correct height. All excess plastic was cut away from the body including the wheel wells. On some of the bodies the rear wheel wells were unmarked and care was taken to cut them out to the right dimensions and in the right place.

Two of each body style was necessary for the set of three experiments: one for the PIV and Lift/Drag measurements and another for the surface pressure measurements. The bodies for the lift and drag and the PIV experiments were painted flat black on the outside to minimize glare from the PIV laser (this step may be omitted if PIV is not to be performed), but the bodies used for the pressure tap experiments required more preparation.

First a set of pressure tap assemblies was constructed and mounted along the centerline of the body on the inside surface of each model. A schematic of the pressure tap assembly is shown in Figure 3. Each assembly consisted of a two foot length of 1/16” Tygon tubing, a 1/16” barbed connector and a small suction cup. A 3/32” hole was drilled through the center of each suction cup and a barbed connector epoxied into it. A two-foot long section of tubing was then epoxied to the other side of the connector making sure not to clog the tubing or the connector. Next, 0.05” holes were drilled along the centerline of each vehicle. The first pressure tap was then placed as far forward on the car as possible. The position of the hole in the connector was noted with a marker, and successive holes were marked such that the suction cups would not interfere with each other when pressed flat to the body. On areas of the car that are horizontal and far from geometry changes the pressure tap spacing was increased in the interest of capturing the pressures in the regions of the most interesting geometry. The holes were then drilled according to the layout and both sides of the surface were sanded down with steel wool to make the openings as smooth as possible.

The final step was to glue the pressure tap assemblies to the underside of the body. We lightly abraded the smooth side of the suction cup with steel wool to aid the adhesion process. A piece of small diameter wire was threaded through each hole to prevent the hole from filling with epoxy during the gluing stage. A small ring of epoxy was put on the outer edge of the suction surface of the suction cup and pressed flat to the body with the wire in the hole of the connector. Once the epoxy hardened the wire was removed and the assembly was complete. Sixteen to eighteen pressure taps were placed along the centerline of each model depending on its centerline length.

**Test Equipment**

Running the experiments requires access to a windtunnel instrumented with a dynamometer system and a pressure transducer (or manometer). A PIV system is necessary for the velocity field data. If one is not available images can be accessed at the Union College website.
The wind tunnel at Union is an ELD open circuit suction tunnel with a 12-inch square by 22 inch long test section. This size test section results in a blockage ratio of approximately 17% for the 1/12 model racecars. The wind tunnel was outfitted with a custom-made splitter plate located approximately 1.5” above the test section floor on which the models were mounted. This placed the cars in the free stream area of the tunnel to limit boundary layer effects.

The wind tunnel is instrumented with a two degree of freedom dynamometer for measuring lift and drag forces. The system uses restrained cantilevered beams and two linear voltage differential transducers whose output is connected to a panel display and to a PC based data acquisition system. The wind tunnel is also instrumented with an MKS Baratron Series 200 pressure transducer with a range from 0 to 10 inches of water. The pressure transducer is connected to a selector valve which allows for one of 9 signals to be connected to the transducer, and a Pitot probe was used to measure the approach flow velocity.

The velocity measurements around each model racecar were found using a TSI Incorporated PIV system. The PIV system consists of a dual mini Nd:YAG laser (30 mJ/pulse @532nm), a computer controlled synchronizer, a PIVCAM 10-30 digital CCD camera, with cross/auto correlation which records 1000 x 1000 pixels and captures at a rate of 30 frames per second (yielding a data rate of 15 hz), image analysis software (Insight), and data visualization program (Tecplot). We used a Rosco 1600 fog machine to generate particles captured in the PIV images. The fog machine was placed at the inlet to the windtunnel with a diffuser at the end to create a high thin sheet of particles.

On average ten different image locations were necessary to fully characterize the flow field around each vehicle. At each image location 200 instantaneous images were acquired and averaged to estimate the mean velocity field. While the other two experiments were relatively easy to setup and perform, the PIV experiments are fairly time consuming. While the PIV adds excellent visual confirmation to the pressure and lift and drag data, the cost and complication may not be practical for every situation. For this reason, the PIV data is available from a Union College website (http://tardis.union.edu/~andersoa/RC_PIV/) for those without access to a PIV system.

**Test Procedure**

This section describes the test procedure for each experiment. Ideally the experiments are run over the course of two or three lab periods as it takes a fair amount of time to set up and calibrate the equipment. It is recommended that the surface pressure measurement experiment is performed in the first week, the PIV experiment in the second week, and the lift and drag measurements during the third week. Depending on the amount time spent on the PIV studies the first two weeks can easily be combined.
Week 1: Surface Pressure Measurements
The first lab exercise is to measure the surface pressure distribution around the vehicle using the pressure-tapped models. The pressure-tapped body and the mounting arm are connected to the chassis. The tygon tubes are passed through a hole in the bottom of the wind tunnel and the mounting beam is attached to the dynamometer (for support only). The tubes from the car are then attached to the low side of the pressure transducer in whatever arrangement is supported by the wind tunnel instrumentation. (It is assumed that the calibration of the transducer has been performed prior to the experiment.) The wind tunnel is set to a desired speed, and the pressures at each tap are recorded. Depending on the ease of acquiring this data, two or three different speeds should be run, but one set of data at a relatively high speed is enough to understand the trends. A typical pressure distribution is shown in Figure 5 and $C_p$ values are shown in Figure 10. All results are discussed below.

Week 2: PIV Tests
To completely map out the flow field around a single vehicle takes about 1-2 hours of data acquisition and about 4 hours of data reduction. For each of the models that were tested 10-20 images sets were taken at locations around the vehicle. This data was acquired before the lab session. During the actual lab session the PIV system was setup and groups of 3-4 students were brought into the wind tunnel for a demonstration of how the system works. We normally concentrate on the flow field in a single area of a vehicle and study the effects of the vehicle geometry in that area. For example, the flow field at the back of the NASCAR model with and without a spoiler or at the base of the windshield are two excellent areas for an interesting demonstration. Complete flow field maps are made available to the students after the lab session. Some example PIV results are presented in Figure 6 and are discussed below.

Week 3: Lift and Drag Measurements
The execution of the lift and drag experiment is quite easy. The dynamometer has to be calibrated, and this is usually done by the instructor to save time during the lab session and insure valid results. With the dynamometer in place and the mounting bracket already attached, the car is placed in the wind tunnel and mounted to the dynamometer. (In the Union wind tunnel the cars have to be mounted slightly off the floor since the dynamometer relies on deflections.) The dynamometer is re-zeroed with the car in place, and the test starts by turning on the wind tunnel to a predetermined speed on the low side of the test range. The free stream velocity is recorded using a Pitot probe and connected to a pressure transducer and the lift and drag forces are recorded. The process is then repeated for a range of airspeeds. A suitable range is 25 to 50 mph as it is within the actual velocities that are experienced by this type of radio-controlled car. If the test velocity is too high, the bodies tend to flutter. Typical data from this type of experiment is shown in Figures 7, 8, and 9 and is discussed below.

Discussion Of Results
Surface Pressure Results
Figure 5 plots the surface pressure distribution around the NASCAR model. This chart shows high pressures (near stagnation) at the front end of the car as the flow stagnates on the front bumper. The pressure drops as the flow speeds up around the front part of the hood. As the flow
approaches the windshield the pressure again rises and approaches stagnation. As the flow goes over the windshield the pressure drops and is fairly steady over the nearly flat roof. As the flow decelerates over the rear windshield the pressure starts to rise and then finally drops off in the recirculation region behind the vehicle.

The pressure distribution in Figure 5 can be normalized by converting the pressure values into pressure coefficient. The pressure coefficient describes the pressure in terms of a non-dimensional quantity. The highest value of the pressure coefficient is 1, which corresponds to stagnation conditions. A pressure coefficient value of zero indicates that the pressure on the surface is equal to the local static conditions and values lower than zero indicate that the pressure is lower than static at that point. Using the pressure coefficient as opposed to pressure values allows the aerodynamic performance of each of the models to be compared to each other directly. Pressure values are dependent on flow velocity and for the most part pressure coefficient is independent of speed over a broad range of flow velocities (provided the flow regime does not change). The characteristics of the body geometry are the sole factor in determining the pressure profile of the vehicles. Pressure coefficient is also a powerful tool when making changes to a vehicle. If a spoiler is added to the back of the NASCAR racer, for example, the profiles could be examined directly and the effects of the change are not confused with variations in air speed or atmospheric pressure conditions.

It is common practice in motor sports to plot the pressure coefficient distribution as negative pressure coefficient, because it makes interpretation of the data easier. On \(-C_P\) charts the lowest value possible is \(-1\) which corresponds to stagnation conditions. The higher the data points on a \(-C_P\) plot corresponds to higher local flow velocity and lower static pressure. It is also easier to assess the lift characteristics of the vehicles. For example, the lower the data points on the \(-C_P\) plot over an area of the car that is not perpendicular to the free stream means that more downforce is being produced over that area of the vehicle and vice versa. Referring back to the example of the NASCAR racer with and without a spoiler, the \(-C_P\) values in the region over the rear half of the car are much lower for the car with a spoiler.

PIV Flow Field Results
Figure 6 shows the velocity field results at the base of the windshield for the Beetle and for the NASCAR racer. The figures are scaled to approximately the same size, and the results show a larger low velocity region at the base of the beetle windshield than that on the NASCAR racer. The more streamlined shape of the NASCAR racecar results in a smaller low velocity region in this area. This is contrasted to the almost 90 degree turn required by the flow over the Beetle windshield which is much harsher than that on the NASCAR racer.

Lift and Drag Data
Figure 7a plots lift and drag force values versus approach velocity and Figure 7b plots the lift and drag coefficients for the hatchback model as defined in equations 1 and 2. Figure 7a illustrates the dependence of the drag and lift force on the velocity. It is also evident that the measured values are on the order of 1-2 N for the drag force and 0.4 to 0.6 N for the lift force. A dynamometer to be used in this type of experiment must be able to measure small force values. Figure 7b shows that the lift and drag coefficients are invariant with velocity for the range of
velocities tested, which indicates that the lift and drag forces are proportional to the velocity squared as per equations 1 and 2.

Figure 8 shows a comparison of the lift and drag forces for all 5 racecar models at an approach flow velocity of approximately 18 m/s. The results show that the NASCAR model has the lowest drag force and the hatchback has the highest drag force. This is due to the smooth contours of the NASCAR racer compared to the sudden geometry changes on the hatchback. The LeMans car has the lowest lift force and the General Lee has the highest lift force. The forces on the LeMans vehicle are quite interesting, because it is the only vehicle experiencing negative lift, or downforce. This is certainly due to the spoiler like kickup at the rear of the vehicle and the high pressure separation region behind the wheel wells. (It should be noted that the NASCAR will produce downforce if fitted with a rear spoiler.)

Figure 9 plots the drag and lift coefficients and shows more defined differences in the lift and drag performances of the vehicles compared to the force plot of Figure 8. While the drag forces were different for each car, normalizing the data to drag coefficient revealed that the drag performances for all of the cars except the LeMans car are nearly the same with the NASCAR exhibiting the lowest drag. Figure 9 shows very clearly the drag penalty that is paid for the outstanding downforce producing capability of the LeMans car, and reveals the underlying theme of aerodynamic design which is to try to produce maximum downforce with minimum drag. It should also be noted that all of the vehicles except for the LeMans car produced positive lift and the Beetle had a lift coefficient closest to zero which is probably the result of the spoiler-like kick-up at the rear of its geometry.

PIV and Pressure Coefficient Results
Figures 10a-10d show the PIV flow field results around the each vehicle. The negative pressure coefficient values as defined in equation 3 are superimposed on the PIV data for each vehicle. The PIV data shows a low velocity stagnation region at the front of each vehicle and an acceleration region at the top of the hood. In all four cases we also see an acceleration region at the front of the roof, and in the case of the hatchback we see two distinct acceleration regions over the roof, the second one caused by a small protrusion towards the back end of the roof. The plots also show large low velocity regions behind each car with a particularly large one behind the hatchback. We also see a large low velocity region at the base of the windshield of the General Lee and the hatchback.

The PIV results help to illustrate the effect of streamlining on drag and the relation between pressure and velocity. The NASCAR model has the lowest drag, and the image of the velocity field shows smaller separation regions and more streamlined flow. The relationship between the velocity and pressure is also confirmed. The PIV results show regions where low velocities correspond to high pressure and vice versa which confirms Bernoulli’s theory that as the velocity increases the pressure decreases.

Conclusion

This laboratory experiment provides an exciting way to teach fundamental principles of fluid mechanics by performing a range of tests on 1/12 scale radio controlled vehicles. The students
learn the relationship between pressure and velocity as described by Bernoulli’s equation. This is accomplished by measuring the pressure profiles over the surface of the vehicles and comparing them to the PIV results. The forces of lift and drag and the geometries that cause different levels of each are also taught. Through comparison of the different body shapes and the resultant drag coefficients it is possible to illustrate the concept of streamlining, and how some shapes are more efficient than others. The concept of lift is explored in the same manner and can be enhanced by testing the cars with spoilers on them to induce downforce. It is also possible to show that the cars with larger high velocity areas over the upper surface have larger lift coefficients, and further solidify comprehension of Bernoulli’s equation. We found these lab exercises to be very successful. The students are excited to be studying race car aerodynamics and the combined use of PIV and pressure/force measurements helps to reinforce key fluid mechanic principles.

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Radio Control Vehicle Company Information:

Bodies

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Figure 1. Schematic showing the airflow paths around a NASCAR racer. Colors of the arrows represent relative flow velocities green being freestream velocity, blue is the lowest velocity, and red is the highest velocity.
Figure 2. The model Race Cars (a) Ford Taurus NASCAR racer, (b) 1969 Dodge Charger (General Lee) (c) baja Beetle and (d) a hatchback (e) Nissan P-35 LeMans Style prototype racer (NOTE: no spoilers were used in the actual tests)
Figure 3. Picture and schematic showing pressure tap instrumentation

Figure 4. Experimental Setup (picture of windtunnel)

Figure 5. Pressure distribution over Nascar Model.
**Figure 6.** PIV Image of Flow (a) at the base of the windshield for the Hatchback Model. (b) for the NASCAR Model

**Figure 7.** The plot of $C_D$ and $C_L$ versus velocity for the hatchback model shows that there is very little variation of the lift and drag coefficients with velocity.
Figure 8. The lift and drag forces at a velocity of 18 m/s show that while the drag force is similar for all models, the lift forces vary quite a bit.

Figure 9. The average lift and drag coefficients for the 5 model cars shows that only the LeMans style car has negative lift (downforce) which is at the expense of a large drag coefficient.
Figure 10a. PIV and pressure results for the beetle.

Figure 10b. PIV and pressure results for the General Lee.

Figure 10c. PIV and pressure results for the hatchback.

Figure 10d. PIV and pressure results for the Nascar.