Optimal Cycling Formation with Respect to Drag

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Abstract:

Throughout this project we have made several observations with systems of stationary bodies and how various formations correlate to drag. Several of the main things we have noticed include; certain separation distances dictate whether the resistance from the drag is either repelling or thrusting the bodies and the trend of the scatter plot, and that plotting drag coefficient vs diameters of separation, is non-linear. We first tested various formations of stationary bodies to test which were the most effective. After testing, we figured out that the straight line formation was the best at reducing drag for the trailing bodies, as the lead body takes most of the gust and shields the trailing bodies from most of the effective drag. We then noticed that when the bodies were farther apart the drag coefficient was higher and when they were more tightly packed the drag coefficient decreased. Some of the finer details we noticed include how the drag coefficient was positive in some cases and negative in other cases, and we observed that a negative drag coefficient meant that there was a negative drag force, thrusting them forward rather than acting against them. **Throughout the various tests, diagrams, and collections of data we have done, we reach the conclusion that the most ideal biker configuration is when each biker is about two diameters in separation apart from one another in a single file line**.

Introduction:

The motivation behind this study is to help cyclists and cyclist groups find the optimal positioning to minimize drag force. This will allow the cyclists to draft off each other better and achieve a faster overall cycling speed, as the effort the trailing cyclists have to put in is much lower.

Problem Statement:

The way we set up the experiment was that we used the distances between bodies as well as positioning of trailing bodies as independent variables, and all other variables stayed constant. Figure 3.1 and 3.2 show the parameters that remained unchanged throughout all simulations, which include for example the Reynolds number and free stream velocity. Our lead body was also placed in the same position each simulation. In addition, all three bodies retained the same shape and size throughout.

```
In [3]: Re = 200; # Reynolds number
        U = 1.0; # Free stream velocity
        U∞ = (U,0.0);

In [4]: xlim = (-5.0,5.0)
        ylim = (-2.0,2.0)
        k = 1.5; # factor to multiply grid spacing by to get point spacing

        Δx, Δt = setstepsizes(Re)

Out[4]: (0.01, 0.005)
```

Figure 3.1: Constants Held Throughout Testing

```
In [6]: basicbody = Ellipse(0.5,0.5,k*Δx)

Out[6]: Circular body with 209 points and radius 0.5
           Current position: (0.0,0.0)
           Current angle (rad): 0.0

In [7]: b1 = deepcopy(basicbody)
        let
            cent = (-4.0,0.0)
            α = 0.0
            global T1 = RigidTransform(cent,α)
        end
        T1(b1) # transform the body to the current configuration

Out[7]: Circular body with 209 points and radius 0.5
           Current position: (-4.0,0.0)
           Current angle (rad): 0.0
```

Figure 3.2: Stationary Body Dimensions and Leading Body Position (Constant)

Methodology:

The software that we used to run simulations was the ViscousFlow package running on Julia language. To actually run the code and document our findings, we used Jupyter Notebooks. As illustrated in Figure 3.1, we used delta x and delta t values of 0.01 and 0.005 respectively, and set step sizes based on the Reynolds number. Our circular bodies consisted of 209 points and radii of 0.5, which can be referenced in Figure 3.2.

Results and Discussion:

To best visualize our findings, Figure 1.1 illustrates a scatter plot that depicts the drag coefficient vs. separation distance (in terms of diameters) and shows how the drag coefficient begins at a negative value and increases to a positive value as separation distance increases. To begin to break down this scatter plot, we can first take a look at the gifs/images correlated to each diameter and see what these data points resemble. Taking a look at Figure 1.2 we see how this visualization is connected to the data points at two diameters separation distance. We can see how the drag coefficient at this separation distance is negative, which means that the trailing bodies are being pulled together. A negative drag force regards a present thrust force. A real life application to this example can be seen when bikers are moving in a tight line formation and the leading rider, or leading body is always directly exposed to the gust and flow field created by the leading body “wakes” behind the trailing body since it is so close, so it causes the gust to actually propel the trialing body closer to the lead body. This allows cyclist teams to work together as a team to move faster as a group, as one person can take most of the drag and the rest do not have to work as hard. Bicycle teams can then switch the lead cyclist to minimize the effort needed.

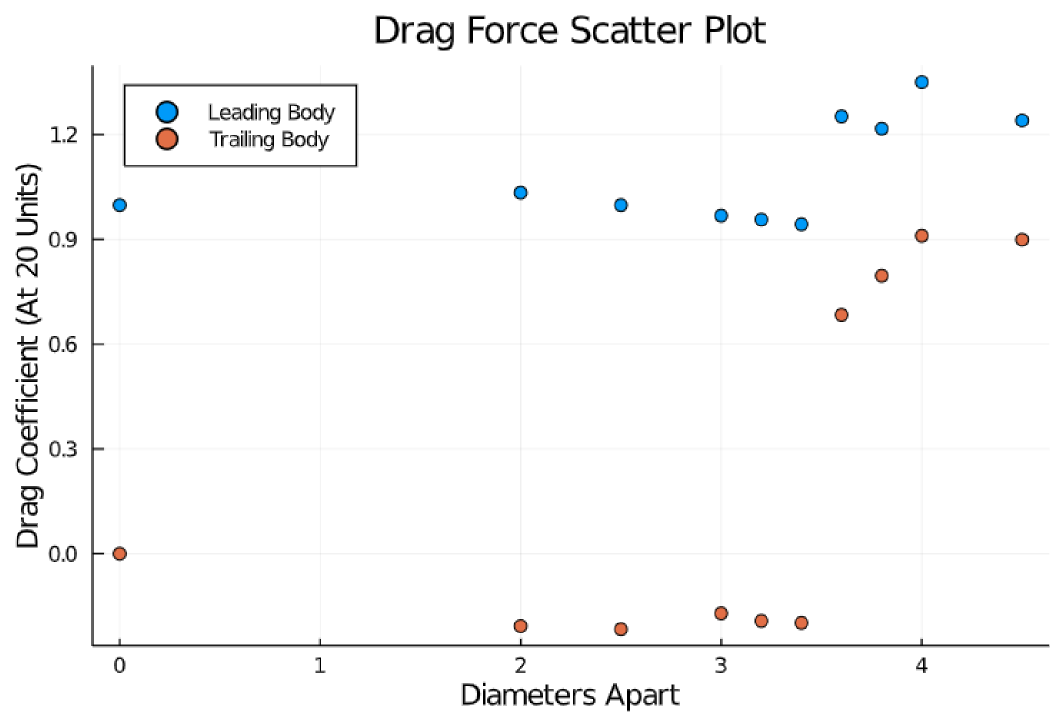

Figure 1.1: Scatter Plot for Drag Coefficient vs Diameters Separation Distance

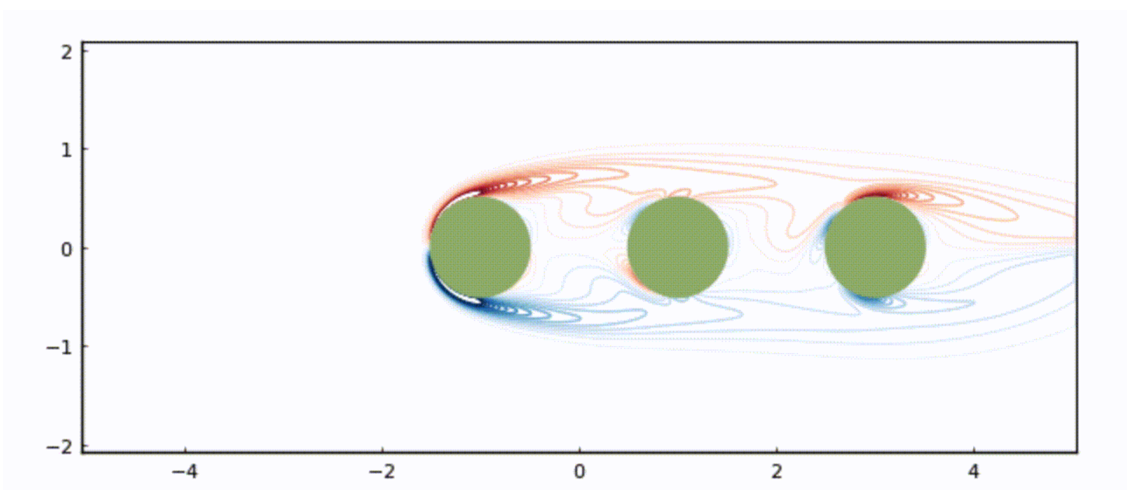

Figure 1.2: GIF of flow field where bodies are 2.0 diameters apart

Rationale:

Addressing the physics behind this phenomena to further explain why two diameters separation distance is the most ideal configuration, we look at the equation for the force of drag: $F_d = \frac{1}{2}$��$v^2 C_D A$ The variables used to calculate drag include a drag coefficient (usually found out experimentally), reference area, velocity, and the density of the fluid where all these variables are directly proportionate to calculating drag. Within our experiment the variables of density of fluid, drag coefficient, and velocity are all constant in every test because the same fluid, same object, and same set velocity is used for every test respectively. The beauty with our equation in particular is the consistency and versatility it holds. For example one of the variables to calculate is the drag force coefficient and this variable is dependent on the Reynolds number where $Re = \frac{\rho u L}{\mu}$. With this formula we notice the drag coefficient is not tied to the velocity, circle diameter, nor density. This is especially powerful because this means that altering any other variables in the drag force formula such as velocity, reference area, or density will result in a proportionate increase in force. Since the coefficient for one trial is the same and not affected by velocity, circle diameter, or density these means that changing those listed variables would mean a proportional increase or decrease in drag force.

For example if we take a look at Figure 1.2 and perhaps change the velocity by a factor of three, since velocity is squared in the drag force formula this means that drag force would increase by a factor of nine. This is all proportional since the coefficient stays constant for the same separation distance and Reynolds, only varying when going to another trial. This is significant to our study because when observing the drag force on our bodies under a certain configuration it will always be a proportional increase or decrease depending on how that certain variable changes. Ultimately, this means that if the velocity, circle diameter, or density of the flow changes in one of the experiments then the drag force will fluctuate the same way regardless of the drag coefficient.

Experimental Error/Challenges:

We did not run into many issues while performing these experiments and collecting data. Most of the time the reason why it might have taken longer to acquire accurate and precise data was due to the calculations, as there are many different calculations that have to take place in order for the simulation to run. There may be an inconsistency in the data, which is shown by the differing drag coefficients of the lead body for all our trials in the scatter plot. While one might think that the drag coefficient for the lead body should always be the same, as there are no independent variables that could affect the lead body's drag coefficient, we believe this is not the case. Our theory is that the fluctuation in drag coefficient for the lead body is likely due to the wake left behind the lead body at time interval twenty convective time units. Since these data points reflect the drag coefficient at twenty convective time units that means that this drag coefficient is being dispersed across the trailing bodies or being lost to outside forces in this open body. Looking at Figure 1.2 and Figure 1.4, you will see that the lead body in the flow field with bodies two diameters separation (Figure 1.2) has a relatively consistent wake that does not fluctuate much. However, looking at the flowfield with bodies 4.5 diameters apart (Figure 1.5), you can see that the wake fluctuates a significant amount. We infer that this is likely due to the fact that in Figure 1.2, the second body stops the wake from fluctuating due to the distance between the two bodies being small enough to prevent the fluctuations that would otherwise happen. As the wake starts to fluctuate, it hits the second body, which develops a new wake.

The drastic jump in drag from 3.4 diameters apart to 3.6 diameters apart can be explained by the wake as well. As we increase the distance apart from one another, there comes a point where the wake behind the lead body breaks before hitting the trailing body, which is likely what causes the drag on the trailing body to spike. In essence, the trailing body gets its own gust that comes from the broken wake that the first body provides. The drag coefficient on the leading body also spikes, as now that the wake left by the lead body fluctuates a large amount the drag coefficient also fluctuates more. The evidence for this is shown by figures 2.1 and 2.2. In figure 2.1, the side force is constantly fluctuating and by a large amount, while in figure 2.2, the side force still fluctuates but does not deviate from the average much. We believe that this demonstrates how the wake breaking/fluctuation affects the drag coefficient so drastically.

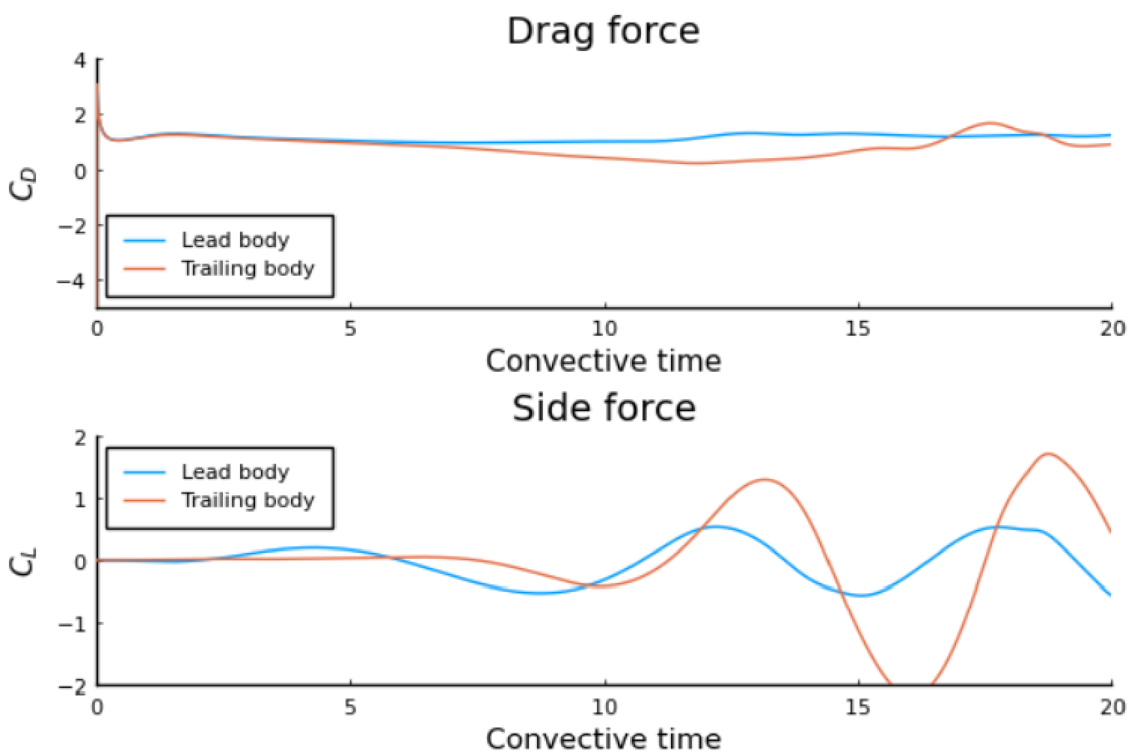

Figure 2.1: Drag and side force for bodies 4.5 diameters apart

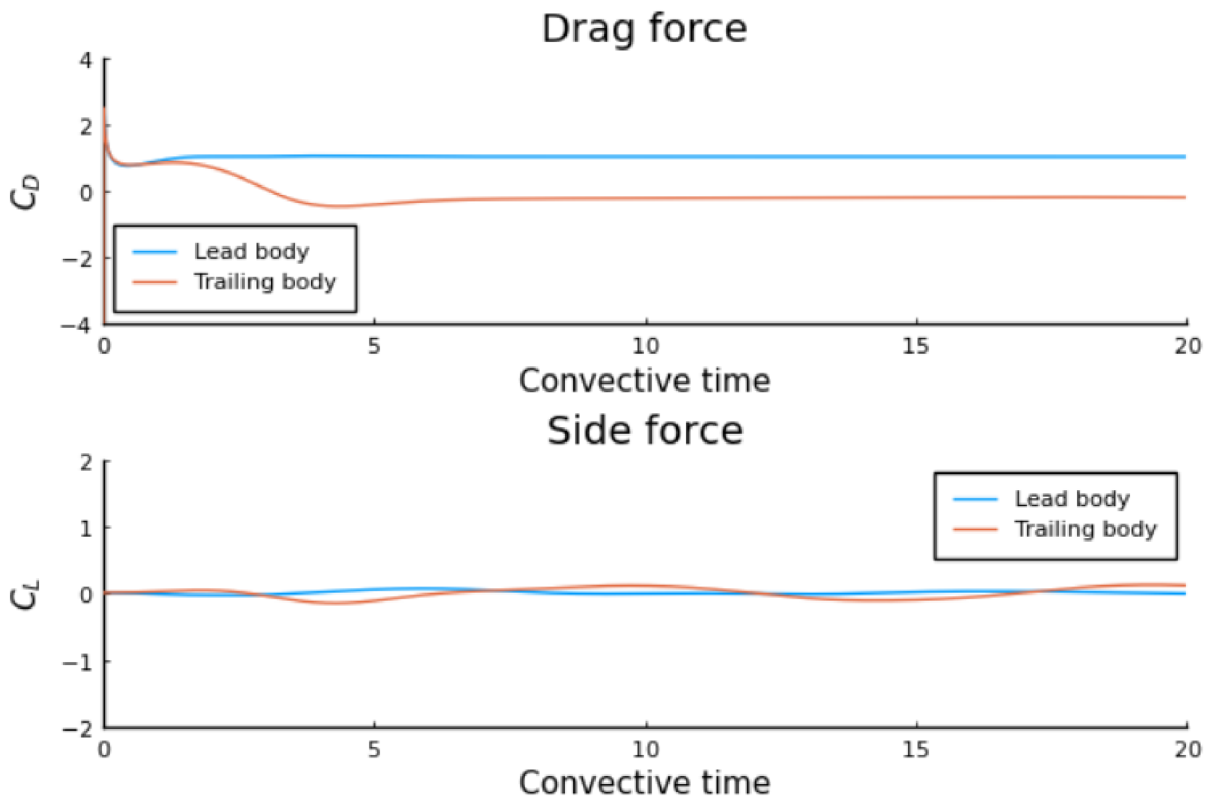

Figure 2.2: Drag and side force for bodies 2.0 diameters apart

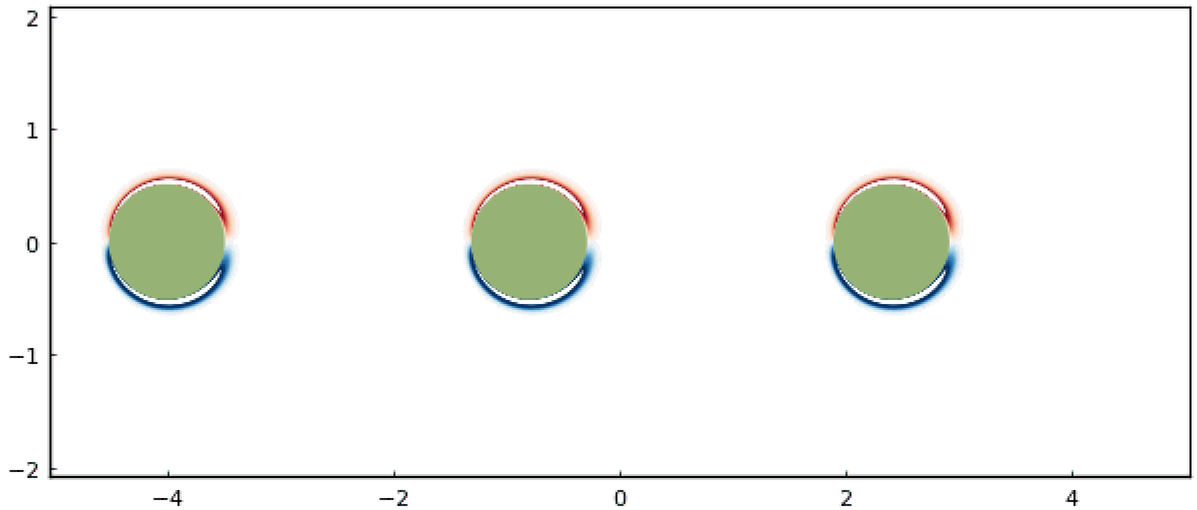

Figure 1.3: GIF of flow field where bodies are 3.0 diameters apart

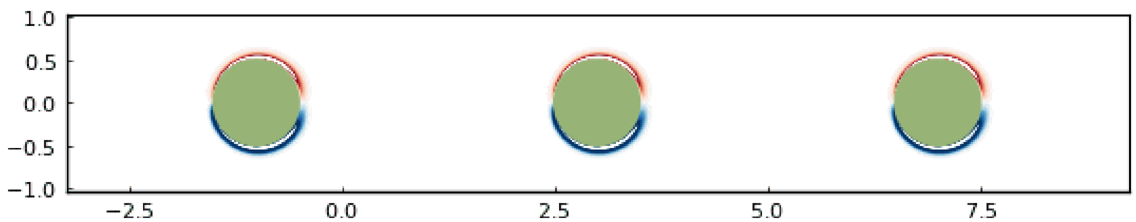

Figure 1.4: GIF of flow field where bodies are 4.0 diameters apart

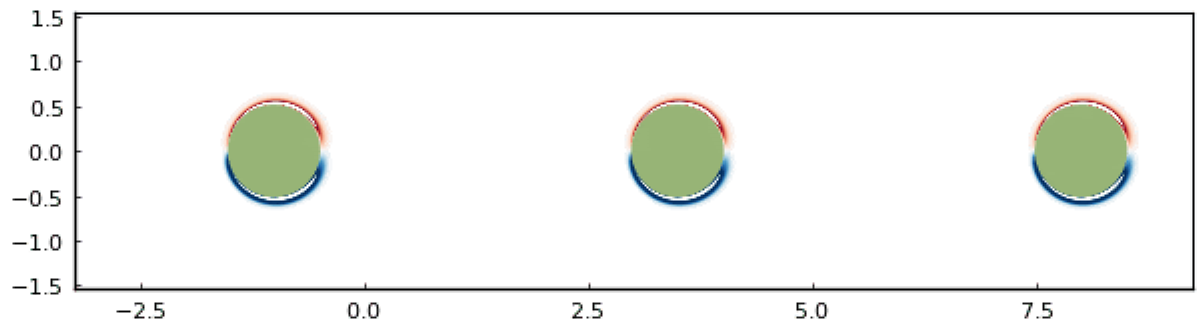

Figure 1.5: GIF of flow field where bodies are 4.5 diameters apart

Conclusion:

After performing these experiments and referencing the equation for calculating drag, we confidently assert that a separation distance of two diameters apart is the best possible configuration for the parameters of the task. Minimizing the drag coefficient of the bodies is the most effective way to minimize drag and is clearly seen through these tests as well. By analyzing the wake of the leading body, we can see how drag changes as the twenty convective time unit interval elapses and how the flow field further illustrates the drag on the trialing bodies over time. The trials were used to find how the drag coefficient is acting on the bodies after the twenty convective time unit frame and then used as data to show a clear relationship in the scatter plot. Two diameters of separation distance is the ideal configuration for a biking group while staying in a tight single file line formation. This formation will eventually result in a thrust force in the same direction as the bikers are going, only aiding their journey in battling the gust.