

UNIVERSITY OF COLORADO - BOULDER

MCEN 5151
FLOW VISUALIZATION

Team First: Get Wet II

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I Introduction

Many of us have tried riding a bike in the rain, and likely invested in a fender soon after. Water gets sprayed up by the rear wheel and all along your back. Our initial plan was to ride through a puddle on various bikes and capture how this spray changed on each. The spray was not as visible as we had hoped, so we pivoted to something more dramatic. This was our first team project for Flow Visualization, as a group of three we get some help from each other setting up and capturing our flow experiment.

II Test Setup

The bike was clamped into a stand by its seat post with a hose held at the bottom bracket. The pedals were turned by another group member while the third captured a video so the wheel speed could be found later.

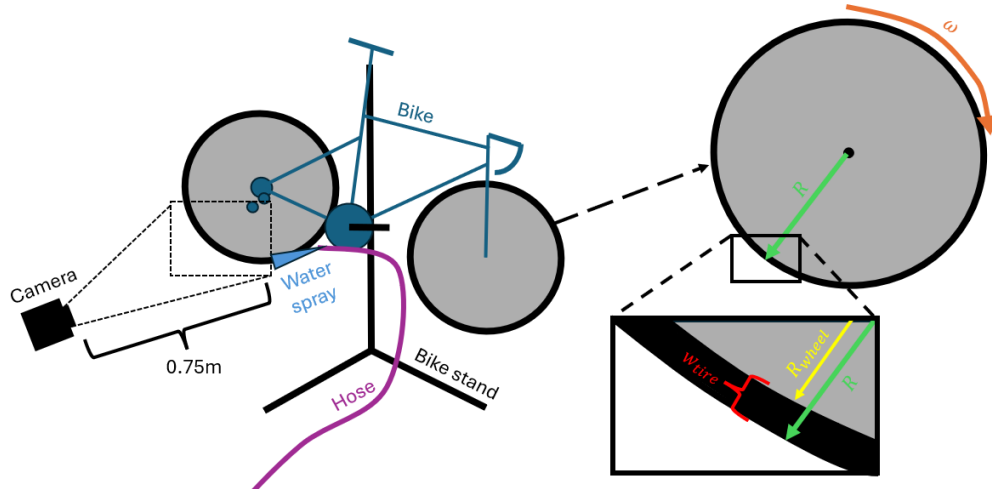


Figure 1: Experiment Setup

We need to solve for some of the dimensions show in the sketch (Figure 1). The wheel is a 700c road wheel. Despite the value used to describe it, the diameter is 622 millimeters, so $R_{wheel} = 0.622\text{m}$. The tire mounted is a 30mm wide Challenge Criterium. Width As Measured (WAM) and Radius As Measured (RAM) can both differ significantly from the label on tire, but for simplicity we will assume the contribution to radius is equivalent to its labeled width, so $w_{tire} = 0.030\text{m}$. This means the total radius is:

$$R = R_{wheel} + w_{tire} = 0.622 + 0.030 = 0.652 \text{ m}$$

The flow rate out of the hose would have been useful for recreating this setup, but we did not have an accurate way to measure this.

III Flow Phenomena

We will begin by estimating the wheel speed. A video was shot using the slow motion function on an iPhone 16 set to 240 fps. The video metadata instead says 214.62 fps, this is the value we will use. The chain stay on the bicycle and decals on the wheel were used as a reference to count 1 rotation, which took a total of 96 frames. This can be used to find the frequency the wheel is spinning at and the corresponding angular velocity.

$$T = 96 \text{ frames} * \frac{1}{214.62 \text{ frames per second}} = 0.447 \text{ seconds}$$

$$f = \frac{1}{T} = \frac{1}{0.447} = 2.236 \text{ Hz}$$

$$\omega = 2\pi f = 2\pi(2.236) = 14.047 \text{ rad/s}$$

Some of the forces acting on a water droplet on the wheel can be seen in Figure 2. This is first shown on a reference frame centered at the middle of the wheel, with gravity acting in the negative y direction and the necessary centripetal acceleration a_c acting along the vector $\vec{R}$. The water droplet is some angle θ from the positive y-axis. Many of the forces here are missing, including the normal force acting on the droplet at the tire and any friction forces. If the water droplet were "glued" to the tire then a_c is the acceleration it would experience towards the center of the wheel as it rotated, but because it is not fixed this is instead the acceleration required for it to remain on the tire. This acceleration must be supplied by some other force.

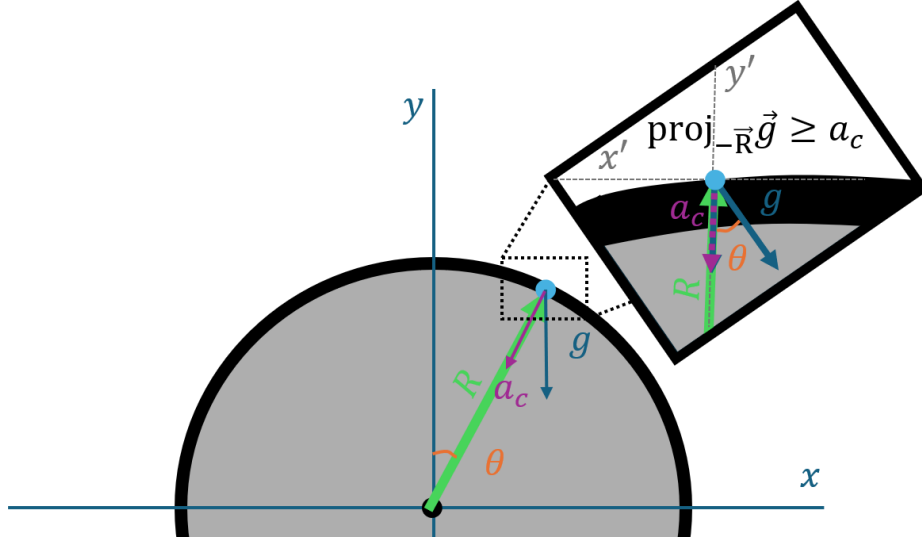


Figure 2: Centripetal Force

We then define a second reference frame centered on the water droplet itself where $\vec{R}$ points in the positive y' direction and x' tangent to the tire. The required centripetal acceleration vector points in the negative $\vec{R}$ direction. It becomes clear that the projection of $\vec{g}$ in the direction $-\vec{R}$ must be greater than or equal to a_c for the water droplet to stay on the wheel:

$$\begin{aligned}\text{proj}_{-\vec{R}}\vec{g} &\geq \vec{a}_c \\ \left(\frac{\vec{g} \cdot \vec{R}}{|\vec{R}|^2}\right)(-\vec{R}) &\geq \vec{a}_c\end{aligned}$$

This looks familiar! If we multiply the numerator and denominator by the magnitude of $\vec{g}$ and pull out the unit vector for $\vec{R}$ we can turn this into the cosine between $\vec{g}$ and $\vec{R}$.

$$\begin{aligned}|\vec{g}|\left(\frac{\vec{g} \cdot \vec{R}}{|\vec{g}||\vec{R}|}\right)\frac{-\vec{R}}{|\vec{R}|} &\geq \vec{a}_c \\ |\vec{g}|\cos(\theta)\frac{-\vec{R}}{|\vec{R}|} &\geq \vec{a}_c\end{aligned}$$

Finally, we know that $\vec{g}$ and $\vec{a}_c$ both act in the same direction, we only care about their magnitudes. Additionally, centripetal acceleration can be defined in terms of some values we already have!

$$\begin{aligned}|\vec{g}|\cos(\theta)\frac{-\vec{R}}{|\vec{R}|} &\geq |\vec{a}_c|\frac{-\vec{R}}{|\vec{R}|} \\ |\vec{g}|\cos(\theta) &\geq \omega^2 R\end{aligned}$$

In my [Get Wet](#) project we had a case come up with the limits of trigonometric values, this is very similar. The $\cos(\theta)$ cannot exceed 1, so this is our critical value. This inspires the choice of a non-dimensional value, the Froude number:

$$\text{Fr} = \frac{u}{\sqrt{gL}} = \sqrt{\frac{u^2}{gL}} = \sqrt{\frac{u^2 R}{R^2 g}} = \sqrt{\frac{\omega^2 R}{g}}$$

The Froude number describes the ratio between the flow inertia and external body forces. Plugging in the values for this problem the Froude number is:

$$\text{Fr} = \sqrt{\frac{14.047^2(0.652)}{9.81}} = 3.621$$

The Froude number is much larger than 1, this means the flow inertia dominates and the flow is described as 'super critical'. What does this mean for our flow? It means there is not a critical angle θ , meaning there is no point where gravity provides sufficient acceleration to keep the water attached to the tire.

So why does the water not come off all at once? There are plenty of smaller forces we neglected here, like surface tension in the water allowing for adhesion between knobs on the tire. We tried a variety of tires, and surprisingly enough mountain bike tires performed the worst. We expect this is because of the large spacing between knobs. The much tighter

knobs on gravel tires or patterns put into the road tires in my photo allow water to stick to the tire better.

All together, the flow we see in the photo makes sense. The sheet towards the right of the image comes from having the water source right next to it. Our calculations were more focused on the droplets seen on the left. These seem evenly spread around the portion of the tire we can see, with no obvious critical angle for their release, reinforcing our supercritical conclusion.

Quantifying how a tire interacts with water can help both in performance and safety. Those at the bike tire manufacturer Rene Herse discuss how much tire design in the cycling world is a 'dark art', realistically serving more for form than function (Heine [1]). They go on to describe the testing and design that went in to three of their tires, a slick, intermediate, and knobby tire, along with the applications for each.

There is much more money in the automotive industry, along with much higher speeds and more frequent accidents. Liang *et al.* [2] have one study of many that attempt to quantify car tire performance. They mapped out the tread pattern for various tires and related them to a few key characteristic parameters for the tire. They found correlations between these parameters and tire performance in wet conditions.

Löwer *et al.* [3] take this a step further by building a model that can predict tire performance during the design phase. They use a FEM model in ABAQUS to estimate how the tire will perform before it has ever been manufactured or tested. They used this strategy to compare multiple designs in wet conditions.

IV Visualization Technique

Our primary visualization technique was manipulating lighting. This was my first time using a flash, and I learned that the camera hot shoe standard is different from most Canons. Thanks to Antonio for letting me use his camera for this project, our flash kits were not compatible with mine.

Using these flashes capped our shutter speed at 1/200s. We hit this limit to freeze the flow as much as possible. From there the primary knob we could manipulate was flash power. I settled on a flash power of 1/16, which froze the droplets but also created path lines for each just before and after the flash triggered. While not perfectly freezing the flow I enjoyed this effect. Antonio used a similar photo with this effect, while Gavin opted for one that completely froze the motion. These photos were taken just before sunset, but the light from other sources was not significant compared to the flash.

V Photographic Technique

I struggled to find a balance with the wheels while taking this photo. They were a bit dirty, but if I had cleaned them they would have reflected even more light. The final photo was edited in DarkTable. Once I started editing everything seemed to blow out the highlights on the wheels, so I tried using masking for the first time. I used a mask that followed the edge of the tire and independently adjusted contrast and sharpness for these two regions. RGB Primary values were also used to reduce some of the green seen in the lower right.

Camera	Canon Rebel T3i	FOV	26.3° (@50mm)
Type	DSLR	Distance to Object	≈ 0.75 meters
Original Image	5202x3464 pixels	Aperture	f/5.6
Final Image	5198x3462 pixels	Shutter Speed	1/200 second
Lens	18-55mm 1:3.5-5.6	ISO	100

Table 1: Photo Specifications



(a) Original RAW Image



(b) Edited Image

Figure 3

VI Conclusion

While we didn't push the limits of any flow phenomena for this first team project, I was able to push my own in both taking these photos and editing them. We did not succeed in our original experiment plan, but all three of us were still able to create photos that I still find very interesting and visually appealing. I would like the opportunity to try our original plan again, perhaps with some more water on the ground after a rain storm. This would also give me more practice with the flash, which I enjoyed using for the first time. I felt like I was finally understanding the settings on my camera, but adding a new dimension with the flash turned the whole thing on its head. The results we saw in tire spray were not what we expected, which has me curious to research tire tread patterns more.

References

- [1] Jan Heine. *The Science of Tire Tread*. Rene Herse Cycles. Jan. 2026. URL: <https://www.renehersecycles.com/the-science-of-tire-tread/> (visited on 10/05/2026).
- [2] Chen Liang *et al.* “A method for tire wet grip performance evaluation based on grounding characteristics.” In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 236.1 (2022), pp. 109–117. DOI: [10.1177/09544070211015880](https://doi.org/10.1177/09544070211015880). eprint: <https://doi.org/10.1177/09544070211015880>. URL: <https://doi.org/10.1177/09544070211015880>.
- [3] Jan Löwer *et al.* “Model for the Pattern-Dependent Wet Grip Prediction of Tires.” In: *Vehicles* 3.1 (2021), pp. 84–110. ISSN: 2624-8921. DOI: [10.3390/vehicles3010006](https://doi.org/10.3390/vehicles3010006). URL: <https://www.mdpi.com/2624-8921/3/1/6>.