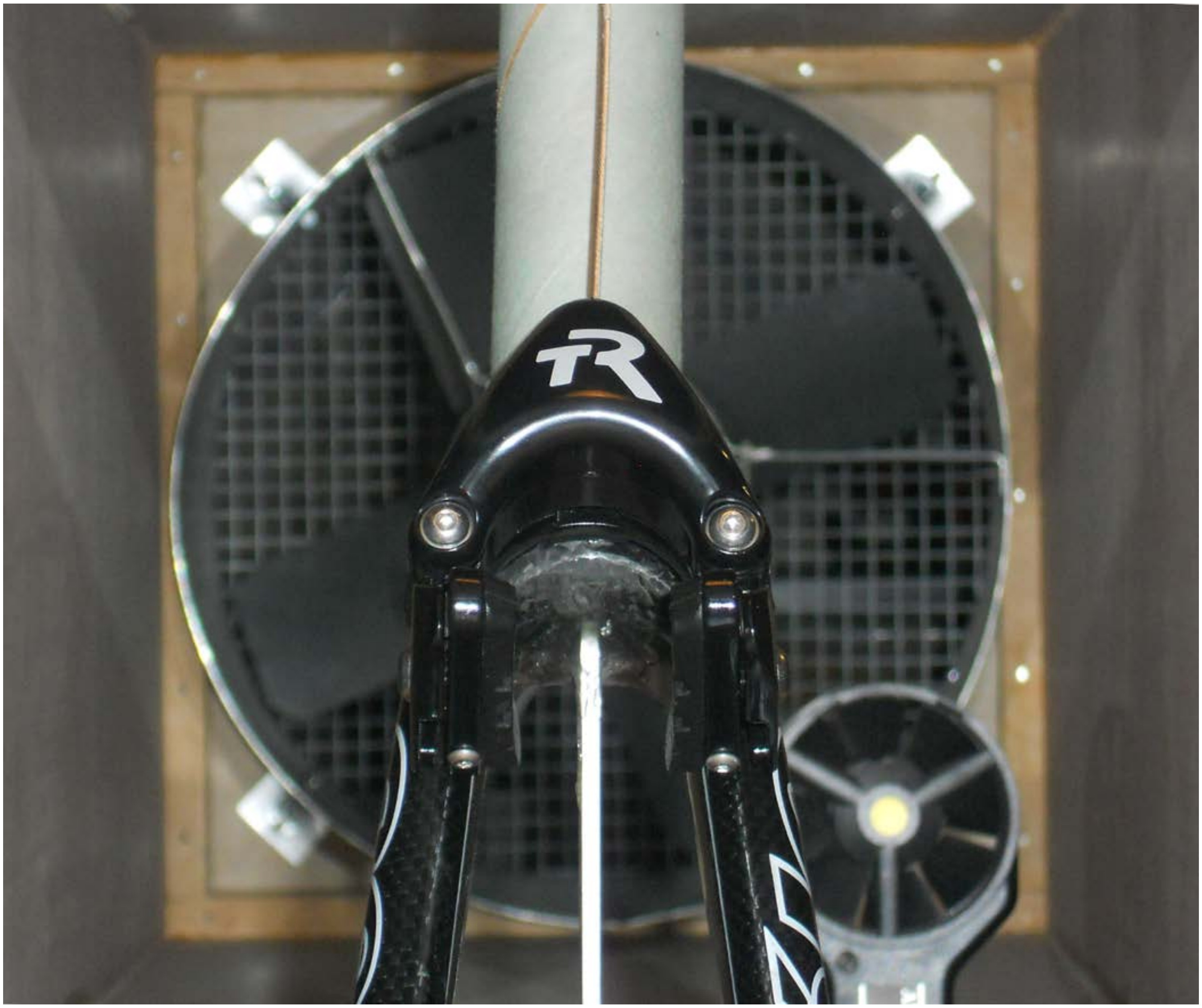
Aerodynamic Testing of Bicycle Brakes



Andrew R. Coggan, Ph.D.

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Introduction

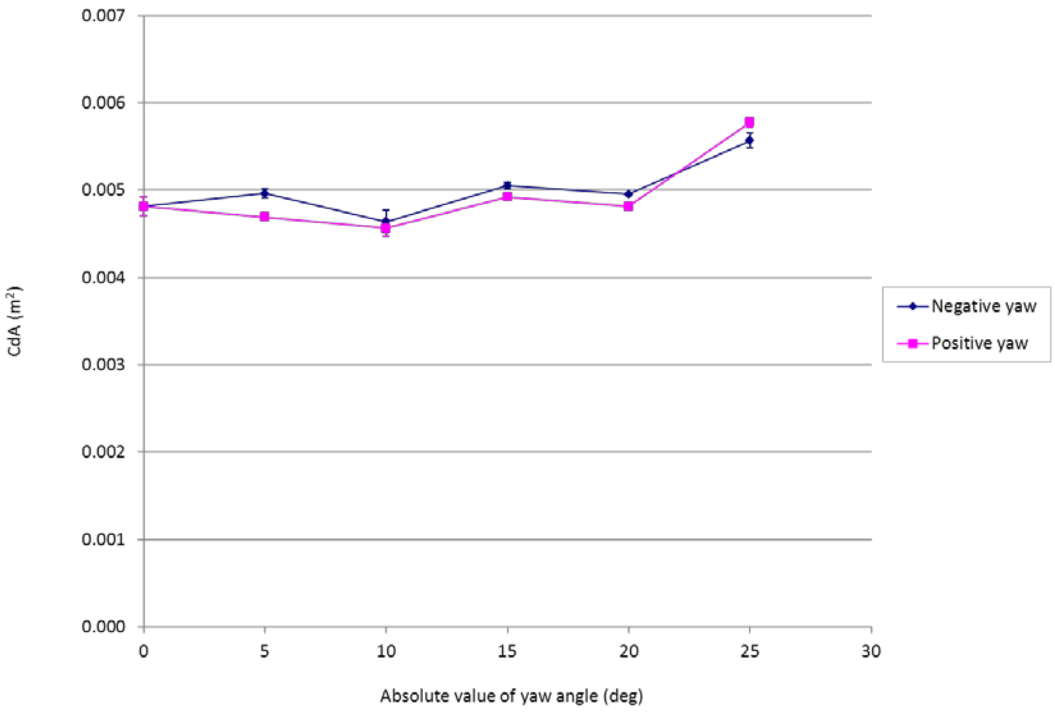
"Aerodynamic" bicycle brakes have been produced off-and-on by various manufacturers since at least the early 1980s, when Shimano first debuted their Dura-Ace AX, 600 AX, and Adamas AX series components. More recently, the introduction of the Simkins Egg brake as well the trend toward proprietary, integrated brakes on time trial (TT) bicycles such as the Felt DA, Fuji D-6, Specialized Shiv, Trek Speed Concept, etc., seems to have rekindled interest in such equipment. Despite this, however, there seems to be very little actual data, at least in the public domain, regarding the efficacy of such brakes in truly reducing aerodynamic drag. Thus, in the summer of 2011 I built a small wind tunnel to try to answer this (and other) questions. The results of my testing are described in this report.

Methods

Data collection

The design, construction, and initial validation of the wind tunnel are discussed here. As part of the present study, I performed additional tests of the wind tunnel to verify performance at non-zero yaw angles, as follows. First, I attached a 30 cm length of fine thread to the end of a bicycle spoke and inserted it through a small hole into the entrance of the test section at various X-Y coordinates. I then took digital photographs from above and counted pixels to determine the angularity of the air flow within the working cross-section. Using this approach, flow was found to differ by <1 deg from ideal at all points tested. Second, I tested a symmetrical airfoil (i.e., an aluminum Cérvelo seatpost) in triplicate at yaw angles ranging from -25 to +25 deg in 5 deg steps, and compared the CdA values obtained at equivalent positive and negative yaw angles. As shown in **Fig. 1** below, nearly identical results were obtained regardless of the sign of the yaw angle, also arguing strongly against any significant deviations or asymmetry in air flow.

Figure 1. CdA of symmetrical airfoil measured at equivalent negative and positive yaw angles.



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Lastly, as a final check I fit polynomial functions to the delta CdA values obtained for each of the symmetrical brakes that were tested (see below), and solved them to determine the yaw angle at which the minimum occurred. This calculation yielded an average value of -0.7±1.2 deg, again confirming the absence of any significant angularity to the flow.

To use the wind tunnel for testing of brakes, I constructed a mount or "sting" out of a prototypical aerodynamically-designed fork (i.e., a 2002 Cérvelo Wolf), as shown in **Fig. 2** below.

Figure 2. Brake sting constructed out of truncated Cervelo Wolf fork.

This fixture was designed to simulate the aerodynamic interactions between the front brake and the fork and head tube of a complete bicycle, while at the same time minimizing drag due to excessive blockage, boundary layer effects, and/or the formation of "unnatural" vortices (e.g., at the ends of the truncated fork legs). While I considered also attempting to simulate the effects of a spinning front wheel, the size of the wind tunnel and the design/location of the balance system made this difficult. Moreover, CFD analyses by others[1] suggested that any interactions between the brake and the wheel should be fairly small, such that testing without one should, at a minimum, still provide useful insight into the relative differences in the aerodynamic performance of different brakes. As it turns out, however, the results I obtained are quite comparable to the limited data available from tests of complete bicycles in much larger wind tunnels[2,3,4], lending credence to their absolute validity. Thus, there appears little reason to believe that the absence of a spinning wheel had a significant effect on the present results.

After constructing the sting and repeatedly measuring its baseline aerodynamic drag characteristics, I tested each brake while it was mounted upon the sting as shown in **Fig. 3** below.

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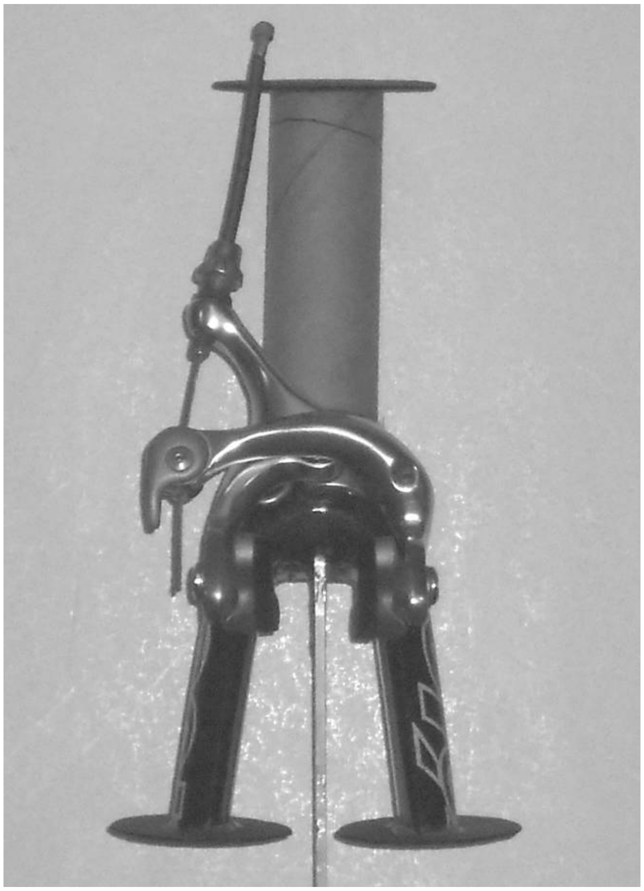
Figure 3. Example of brake mounted on sting.



As shown in the figure, a piece of cable (± housing, depending on the brake's design) extending to a point 120 mm above the center bolt was attached to each brake. This piece of cable also served to maintain the spacing between the brake pads at 24 mm. The distance between the brake center bolt and the brake pads was also kept constant at 40 mm. I tested each brake on at least two separate occasions, with the effective frontal area (i.e., CdA) measured 6-16 times each at (in random order) yaw angles of -15, -10, -5, 0, 5, 10, and 15 degrees. The mean (±SD) coefficient of variation of these measurements was 1.7±1.0%. I also tested some brakes at additional yaw angles, without any cable attached, with the brake pads removed, with modeling clay or electrical tape used to smooth over discontinuities, and/or with chemical fog blown over them to better understand their aerodynamic behavior (see **Discussion**). In total, nearly 1000 wind tunnel runs were performed in generating the data that form the basis for this report.

I tested the following brakes:

1. Shimano Dura-Ace (BR-7700)
2. Tektro R725R
3. Tektro T726R
4. Cérvelo Mach II
5. Dia-Compe BRS 500
6. MRC Aero-Link
7. Simkins Egg
8. Magura RT8 TT
9. TriRig Omega
10. Shimano Dura-Ace AX (BR-7300)
11. Hooker Aero SL

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I selected these brakes due to their popularity, availability, and/or perceived or claimed “aeroness”, and to provide a wide range of designs, e.g., sidepull vs. centerpull. Note that although the two Tektro models are technically rear brakes, they can (and have) been used on the front by substituting a longer mounting bolt. The introduction of the centerpull T725R appears to have made the original R725R less popular among TTers and triathletes, but nonetheless I still included the latter brake to help assess the impact of the cable and “noodle” on aerodynamic drag, as other than their means of actuation the two brakes are identical. Also note that the Magura is technically a “centerpush” rather than a centerpull brake, and more importantly is not truly symmetrical with respect to the bicycle centerline – the implications of the latter are considered in the **Discussion**.

In addition to the above testing, I also photographed each brake plus fork combination when placed directly in front of a known reference area equivalent to the cross-section of the wind tunnel test section (i.e., 305 mm x 305 mm). I then printed these photographs in duplicate on card stock and determined the overall frontal area (A) via the cut-and-weigh method using a laboratory balance with a minimal resolution of 0.00001 g. The mean coefficient of variation of these measurements was 1.2±0.8%. I then used these data to 1) correct the CdA measurements for wind tunnel blockage, and 2) to assess the relative importance of differences in A vs. differences in the coefficient of drag (Cd) in determining differences in CdA (see below).

Data analysis/presentation

Wind tunnel data are commonly presented by first subtracting the drag of the test fixture alone (i.e., the “wind on” tare), followed (when multiple measurements are made) by calculation of the mean and standard deviation or standard error of the resulting values. This approach, however, assumes that 1) the aerodynamic drag of the fixture is known exactly, and 2) there is little or no aerodynamic interaction between the object being tested and fixture to which it is attached. In reality, however, the drag of the fixture or sting is never known with absolute certainty. More importantly, in the present experiments the sting was deliberately designed to interact with the object (i.e., brake) being tested, so as to mimic the aerodynamic behavior of a complete bicycle. Because of the above considerations, in the present article I have chosen to present the data as *delta* CdA values (in m^2) vs. the sting alone, with the *total error of the measurement* calculated using standard propagation-of-error techniques. For completeness, however, the raw data upon which these values are based have been included in the **Appendix**.

To help place the above results in context, I also used the delta CdA values to estimate the time differential (savings) that would result from using each brake (or no front brake at all) in a 40 km TT or 180 km triathlon bike leg. These calculations were made using our validated model of the physics of cycling[5], based on the following assumptions: total (i.e., cyclist + bicycle) mass = 85 kg, coefficient of rolling resistance = 0.004, drivetrain efficiency = 97.5%, air density = 1.185 g/L, CdA and power = 0.225 m^2 and 300 W or 0.250 m^2 and 225 W for 40 km and 180 km, respectively. These assumptions resulted in predicted baseline times (i.e., using a standard front brake) of 54:29.6 for 40 km and 4:39:48 for 180 km. It should be noted, however, that the magnitude of the predicted time savings are largely independent of these starting assumptions.

Finally, as indicated above I assessed the relative importance of differences in A vs. differences in the coefficient of drag (Cd) in determining differences in CdA by regressing the delta CdA values against the increase in A with each brake.

Results

Figs. 4 and **5** display the delta CdA values as a function of yaw angle for each of the 11 brakes tested, whereas **Figs. 6** and **7** illustrate the resulting predicted time differentials in a 40 km or 180 km time trial, respectively. **Fig. 8** shows the relationship between increases in frontal area and increases in CdA.

Figure 4. Delta CdA of sidepull brakes.

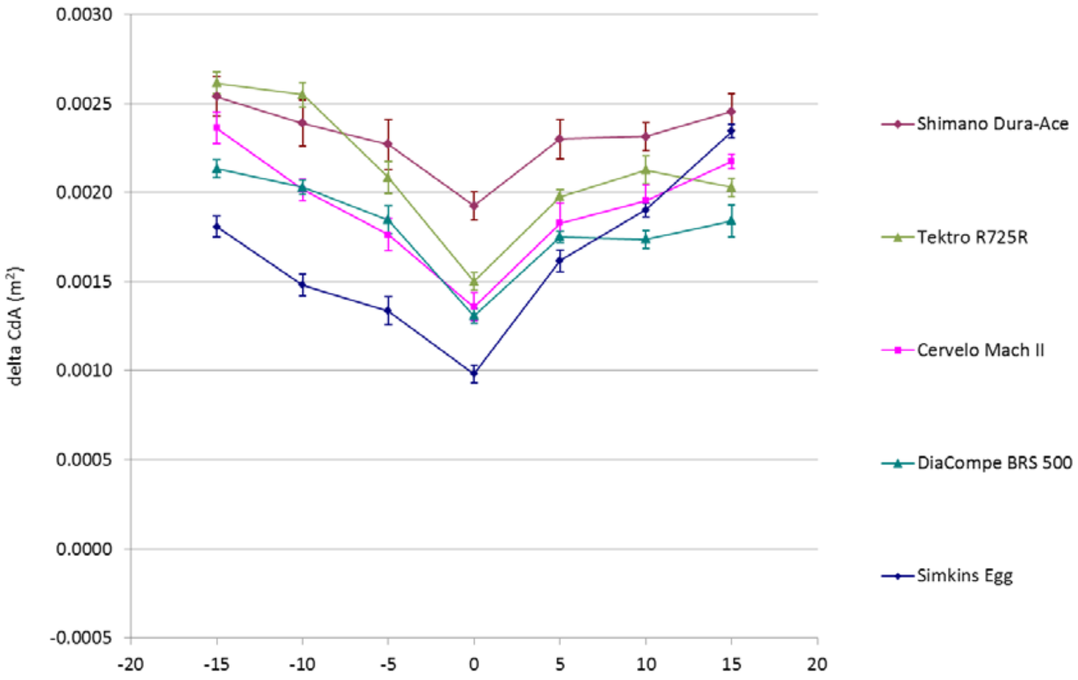

Figure 5. Delta CdA of centerpull brakes.

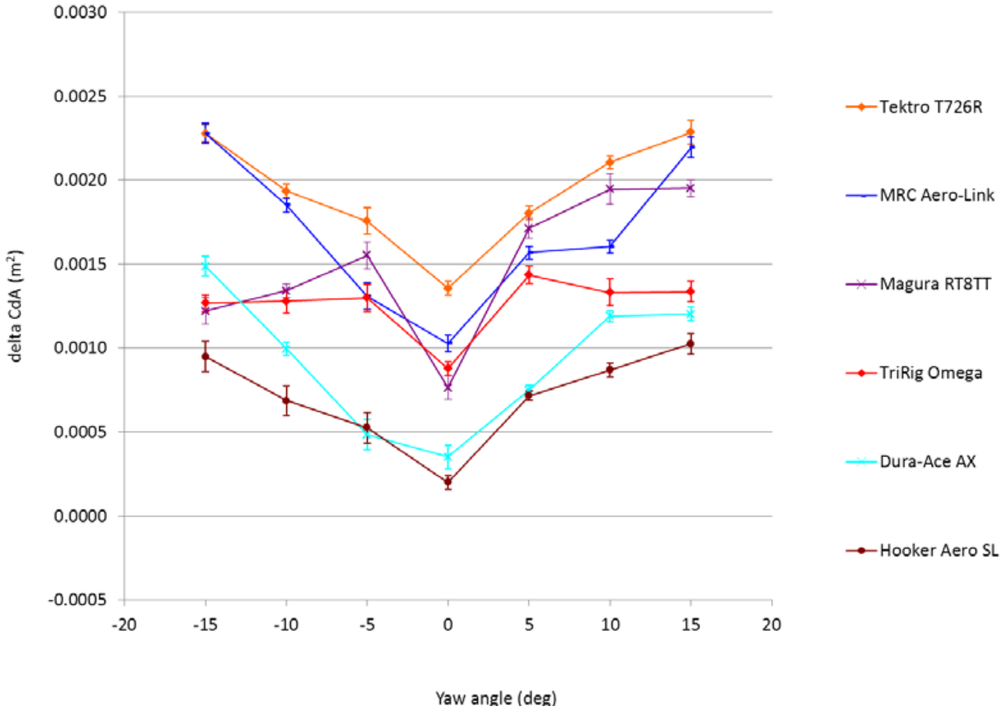

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Figure 6. Predicted time savings in a 40 km TT when using different brakes.

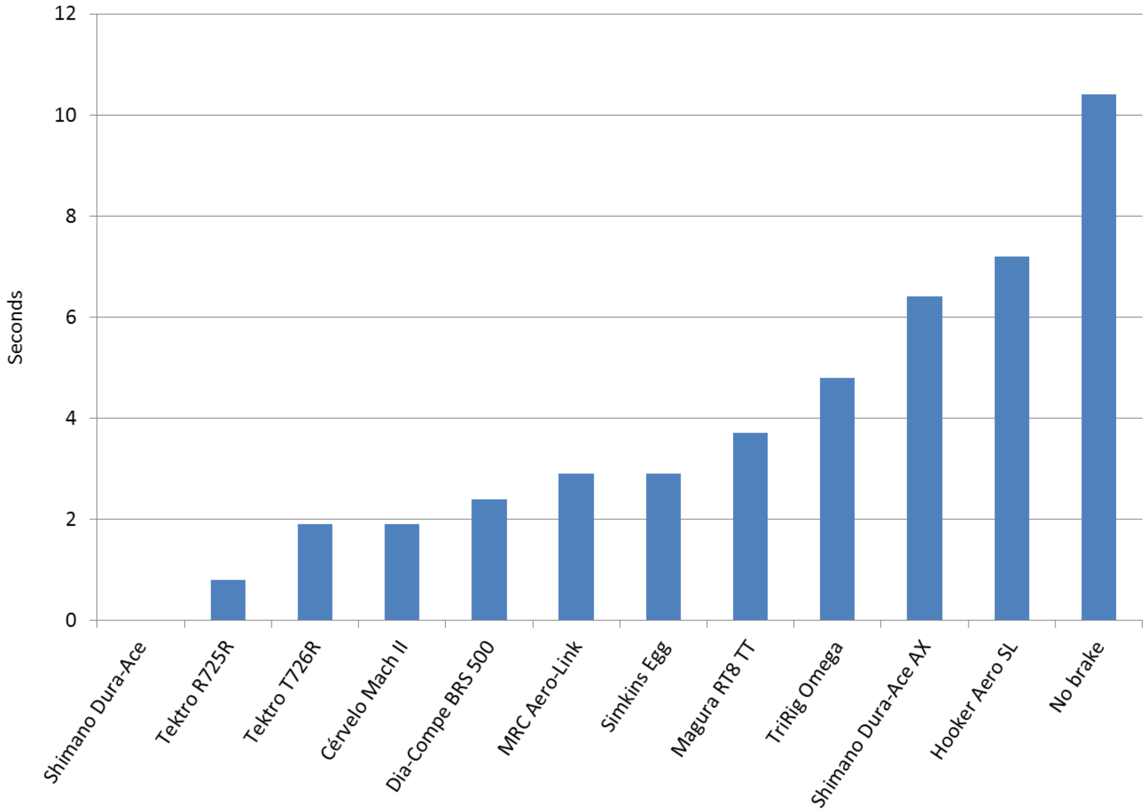

Figure 7. Predicted time savings in a 180 km TT when using different brakes.

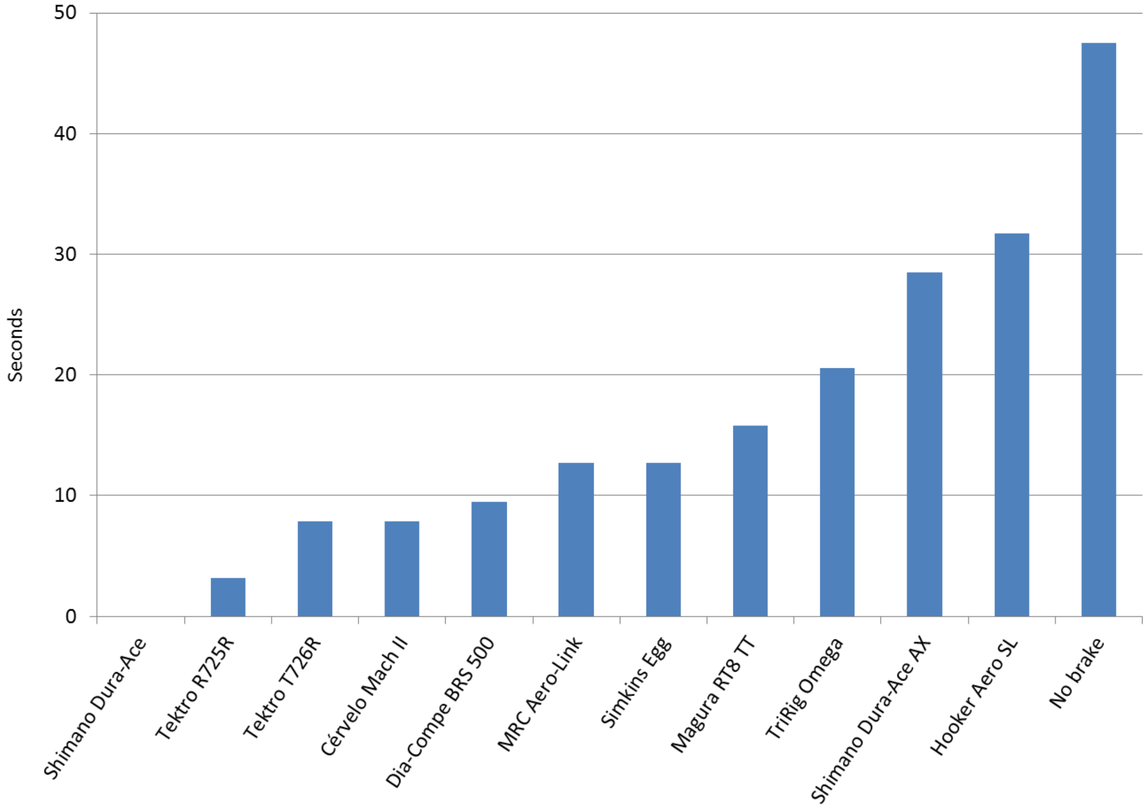

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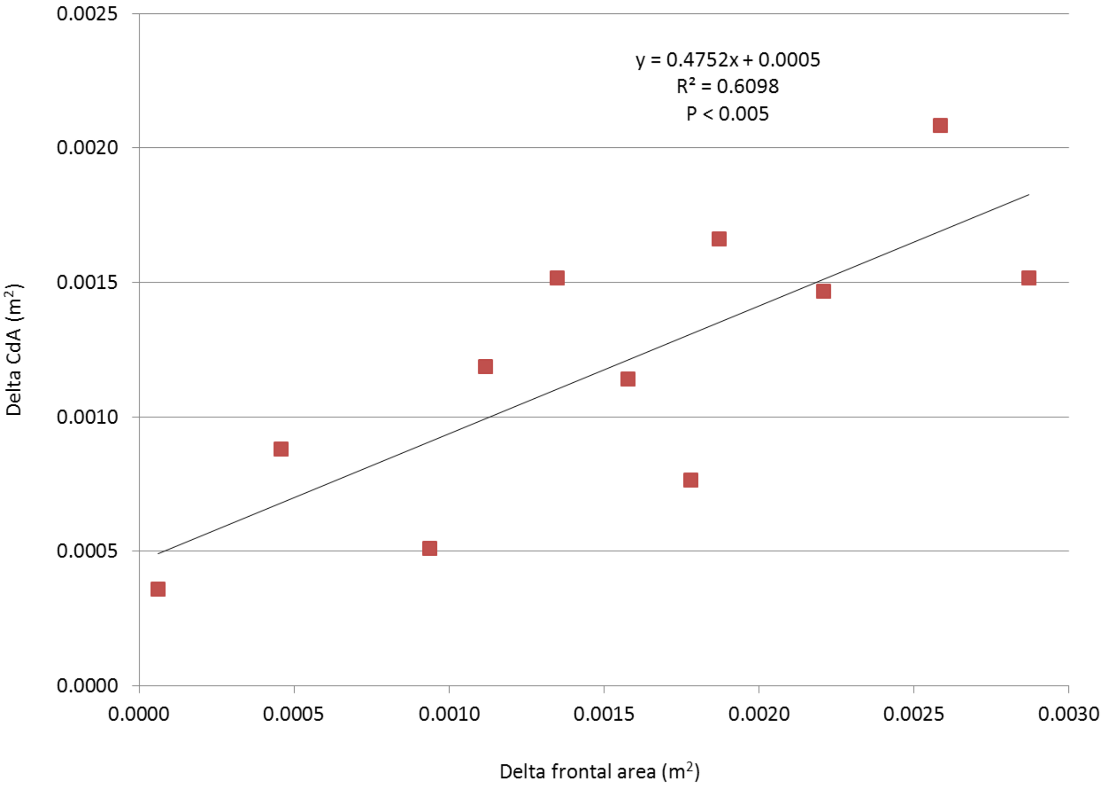
Figure 8. Relationship of delta CdA to delta frontal area at 0 deg of yaw.



Discussion

The purpose of this project was to obtain independent, objective data regarding the aerodynamic drag characteristics of various bicycle brakes. To that end, I built a small wind tunnel, carefully validated it, then used it to test 11 different brakes mounted on a sting designed to simulate the fork, fork crown, and head tube of a complete bicycle. Although my primary goal was simply to quantify relative differences in the aerodynamic performance of various brakes, in absolute terms my results proved to be quite similar to the limited data available from previous full-scale wind tunnel tests.[2,3,4] More importantly, though, I found small, but nonetheless potentially significant, differences in delta CdA between different brakes (**Figs. 4** and **5**). From these data, it can be estimated that, compared to a standard brake, use of an aerodynamically-designed brake could save a cyclist as much 7.2 s in a 40 km TT (**Fig. 6**) or a triathlete as much as 31.7 s in a 180 km Ironman bike leg (**Fig. 7**). Although representing a difference of only 0.2%, races have often been won and/or records have often been broken by comparably small margins. Thus, any cyclist or triathlete wishing to maximize their chances of success in the "white hot crucible of competition" could potentially benefit by choosing their front brake on the basis of the present results.

While the most obvious application of the present results would be in deciding which of the tested brakes to use, the data may be valuable in other contexts as well. For example, knowing that a standard brake increases CdA by ~0.002 m^2 vs. no brake at all (**Fig. 4**) should help place in context any manufacturers' claims for TT/triathlon bicycles with integrated front brakes, and thus allow potential purchasers to make more informed decisions regarding their choice of frameset itself. As well, by providing insight into what actually constitutes an aerodynamic brake, the present results may be useful to anyone attempting to design a new one. The remainder

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of this discussion therefore focuses on apparently *why* some brakes were more aerodynamic than others, rather than simply on *which* brakes were most aerodynamic.

Effect of brake size (design)

As shown in **Fig. 8**, differences in incremental frontal area accounted, on average, for ~60% of the difference in delta CdA between different brakes. As a corollary, on average sidepull brakes had higher delta CdA values than centerpull (or center-activated) designs (e.g., 0.00157±0.00034 vs. 0.00087±0.00043 m^2 at 0 deg of yaw; $P<0.05$), due to their greater (again, on average) incremental frontal area (e.g., 0.00222±0.00052 vs. 0.00095±0.00062 m^2 at 0 deg of yaw; $P<0.01$). This was especially evident at negative yaw angles, i.e., when the effective width of the gap between the side arm/brake cable and the head tube was the greatest, such that the side arm/brake cable was more aerodynamically "isolated". Even the Tektro R725R, which lacks a side arm but is activated by a side-entry cable noodle, exhibited a higher delta CdA value at negative vs. positive yaw angles, especially in comparison to its center-activated cousin, the Tektro T726R. On the other hand, for the centerpull brakes the delta CdA-vs.-yaw relationship was generally symmetrical, as would be expected. The primary exceptions to these generalizations were 1) the Simkins Egg brake, which unlike other sidepull/dual-pivot brakes exhibited highest delta CdA values at positive yaw angles, 2) the MRC Aero-Link, the delta CdA of which was approximately one-third higher at -10 vs. +10 deg of yaw, and 3) the Magura RT8 TT, which like the Simkins Egg also had a higher delta CdA at positive vs. negative yaw. The apparent reason for the anomalous behavior of the Simkins Egg brake is discussed below, whereas that of the MRC Aero-Link and Magura RT8 TT are considered in the next section on brake shape.

The results obtained for the Simkins Egg were surprising not only because of the marked increase in delta CdA at positive yaw angles, but also because Tom Anhalt (who kindly loaned me his Simkins Egg and Cérvelo Mach II brakes for testing) had previously calculated a much larger reduction in aerodynamic drag based on data from field tests using a powermeter.[6] I therefore conducted additional tests in an attempt to ascertain the source of this discrepancy. First, I used a Halloween fog machine to visualize the flow around the Simkins Egg when mounted on the sting. These experiments suggested that the increase in delta CdA at positive yaw angles might be due to interaction between the brake cable and head tube, with their closer-than-normal proximity effectively increasing the width and hence frontal area of the object the air had to pass around. To test this hypothesis, I therefore measured the delta CdA of the Simkins Egg without any cable or cable housing attached. At yaw angles of ≤0 deg, the reduction in delta CdA was comparable to that expected based on theoretical considerations (i.e., based on the length and diameter of the absent cable housing, and the CdA of a short cylinder in a free stream of air at the Reynolds number used in these tests), but at yaw angles of ≥5 deg the reduction in delta CdA was roughly twice as large as predicted (data not shown). Other sidepull brakes were also tested without any cable or housing, but did not show this same pattern, i.e., the reduction in delta CdA was generally uniformly across yaw angles. Hence, it appears that the aerodynamic performance of the Simkins Egg was compromised at positive yaw angles by the location of the brake cable/cable housing. This suggests that, if a sidepull design is used, it is better to have the brake cable as far away from the head tube as possible, even if the housing itself creates a small amount of additional drag. In this context, it is interesting to note that the field tests were conducted with a somewhat unusual cable routing (and, due to the low wind conditions, at close to 0 deg of yaw).[cf. Fig. 3B of Ref. 6] Alternatively, however, it is also possible that the difference between the present wind tunnel measurements and previous field test results for the Simkins Egg is simply be due to the well-known vagaries of the latter approach. Indeed, the variability reported for the Cérvelo Mach II brake in the field tests

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was ~20x greater than that obtained in the present experiments, and approximately equal to the reported difference between the Cérvelo Mach II and Simkins Egg brakes.

Effect of brake shape

Although differences in incremental frontal area accounted for most the differences in delta CdA between brakes, the actual shape of each brake clearly also played a role. This is perhaps most evident in the case of the MRC Aero-Link, which, despite being symmetrical with respect to the bicycle centerline, exhibited a higher delta CdA at -10 vs. +10 deg of yaw as described above. Further measurements at -12.5 and +12.5 deg of yaw demonstrated that, due its flat front/sharp contours, this brake "stalled" markedly at around ±10-12.5 deg of yaw, with small irregularities in the angularity of the flow and/or in the exact positioning of the brake/sting resulting in an asymmetrical delta CdA curve. In contrast, more smoothly shaped brakes such as the DiaCompe BRS 500, Simkins Egg (when tested without a cable), or the TriRig Omega exhibited less of an increase in delta CdA with increasing yaw angle (see more below).

Like the MRC Aero-Link, the Magura RT8 TT also demonstrated an asymmetrical delta CdA response, with delta CdA being lower at -15 and -10 deg vs. -5 deg of yaw, but increasing progressively at increasingly positive yaw angles. As discussed previously, however, unlike the other center-activated brakes the Magura RT8 TT is not truly symmetrical with respect to the bicycle centerline, with one upper arm being slightly larger than the other and each containing a different number and location of "windows" or slots in their sides to allow clearance for the activating mechanism. As well, in the present experiment all brakes were compared at a fixed spacing between the brake pads of 24 mm, which in the case of the Magura RT8 TT required that the upper half of the brake not be fully closed.[*] These factors may explain the asymmetrical delta CdA curve, as well as the fact that the Magura RT8 TT did not perform as well in the present tests (i.e., average delta CdA over -15 to +15 deg of yaw = 0.00150 m^2) as previously reported by Cérvelo[4] (i.e., average delta CdA over -20 to +20 deg of yaw = 0.00064 m^2), even though the results obtained for standard sidepull (delta CdA = 0.00231 vs. 0.00218 m^2) or "scissors" style cantilever (i.e., 0.00193 vs. 0.00145 m^2) brakes were much more comparable, especially taking into consideration differences in the shape of the latter brake.[†] If so, this implies that any end users would need to install their Magura RT8 TT brake carefully to obtain maximum aerodynamic benefit. Alternatively and/or in addition, since the Magura RT8 TT was designed as part of an entire brake/fork/frame system, it is possible that it simply performs better when mounted upon a wider fork (especially when used with the non-UCI-legal cover found on the P5-Six).[cf. p.10 of Ref. 4] A mismatch in brake and fork width, however, would not explain why other brakes that are even broader across the "shoulders" (e.g., Shimano Dura-Ace AX) performed better than the Magura RT8 TT in the present tests. It seems unlikely that the absence of a spinning wheel accounts for the discrepancy between the present and previous results, since there is nothing really unique about the shape of the lower arms or underside of the Magura RT8 TT that might influence any such interaction, and the results

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[*] Magura/Cérvelo recommends that the brake be installed with the hydraulic piston completely retracted, such that the upper arms are in contact with each other and thus more fully conceal the operating mechanism. However, this prevents use of the quick-release function provided on the brake lever (not needed with wider rims), and would require 6 mm of spacers behind each brake pad holder to reduce the spacing between the pads to 24 mm. The configuration tested – with 2 mm of spacers behind each brake pad holder and the upper arms spread slightly apart – therefore may more faithfully represents how the brake would actually be used, at least with standard width rims, and in fact closely mimicked the way the brake was installed on the Cérvelo P5 that Ryder Hesjedal rode in the 2012 Giro d'Italia.[cf. Fig. 24 of Ref. 4]

[†] Based on Fig. 22 of Ref. 4, Cérvelo appears to have tested a TRP T925R brake, which has much more profiled or sculpted arms than the Tektro T726R used in the present study.

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obtained with other brakes were quite comparable in both tests (as well as to other tests of complete bicycles with spinning front wheels[2,3]).

TriRig Omega

As I was beginning this project, I learned that Nick Salazar of TriRig.com intended to produce an aerodynamic brake that would better accommodate the wider rims recently introduced by Zipp, etc. I therefore contacted Nick to offer my assistance, and he quickly agreed to provide prototypes of his Omega brake for testing and to commission a final report. Among the design changes he made in response to my findings were 1) reducing the overall size of the brake, since variations in incremental frontal area *per se* accounted for over half of the variation in delta CdA between brakes (cf. **Fig. 8** and above discussion), and 2) reshaping of the face plate to improve aerodynamic performance, especially at higher yaw angles. (Note in **Fig. 5** how the Omega is the only brake to exhibit a flattening or even a reduction in delta CdA as the yaw angle decreases/increases beyond ±5 deg.) Ultimately, the production Omega proved to be more aerodynamic than all but the no-longer-produced Shimano Dura-Ace AX and Hooker Aero SL brakes, both of which apparently derive at least part of their low drag from the use of non-adjustable, “shortie” brake pads and holders. (The performance of the Dia-Compe BRS 500 may also be due in part to its brake pads, since I had retro-fit it with small, one-piece combination brake pads/wheel guides when using it on my own bicycle.) Importantly, the delta CdA of the Omega proved to be independent of the spacing between the brake pads or the distance it was mounted from the fork, and was actually slightly lower when the brake was fitted with the optional cable hanger vs. when used with a bare cable (data not shown), apparently due to beneficial interaction between the cable hanger and the trailing “head tube”.[cf. Ref. 7] The latter interpretation is supported by 1) the low delta CdA of the Dura-Ace AX brake, which has an integrated cable hanger similar to the Omega’s, and more significantly 2) the fact that adding a comparable cable hanger to the Hooker Aero SL brake resulted in a measurable reduction in delta CdA at all but -5 and +5 deg of yaw (data not shown). In any case, the robust nature of the results obtained with the Omega means that it should have minimal aerodynamic drag regardless of the exact equipment (e.g., wheel) with which it used and/or precisely how it is mounted.

Summary and Conclusions

The purpose of the present project was to obtain independent, objective data regarding the aerodynamic drag characteristics of front brakes. To do so, I built a small wind tunnel, carefully validated it, and used it to measure the increase in CdA resulting from mounting various brakes on a truncated fork. The results demonstrated small, but nonetheless potentially significant, differences between brakes, with use of the most vs. least aerodynamic brake tested theoretically saving a cyclist >7 s in a 40 km TT or a triathlete >30 s in 180 km Ironman bike segment. The present results may be useful not only to athletes trying to optimize their brake selection but also to manufacturers attempting to design more aerodynamic equipment.

Acknowledgements

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Appendix: Summary of CdA values (in m^2) for each brake+fork combination.

	Yaw angle (deg)							
Brake	**-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**Mean**
Shimano Dura-Ace (BR-7700)	0.00761 ±0.00010	0.00761 ±0.00013	0.00755 ±0.00011	0.00758 ±0.00007	0.00754 ±0.00011	0.00760 ±0.00008	0.00770 ±0.00009	0.00760 ±0.00002
Tektro R725R	0.00768 ±0.00003	0.00777 ±0.00006	0.00736 ±0.00004	0.00715 ±0.00003	0.00721 ±0.00003	0.00741 ±0.00008	0.00727 ±0.00003	0.00741 ±0.00009
Tektro T726R	0.00735 ±0.00002	0.00715 ±0.00003	0.00703 ±0.00001	0.00701 ±0.00002	0.00704 ±0.00003	0.00739 ±0.00003	0.00753 ±0.00006	0.00722 ±0.00008
Cérvelo Mach II	0.00743 ±0.00008	0.00724 ±0.00005	0.00704 ±0.00005	0.00701 ±0.00011	0.00707 ±0.00009	0.00724 ±0.00009	0.00742 ±0.00002	0.00721 ±0.00007
Dia-Compe BRS 500	0.00720 ±0.00001	0.00725 ±0.00003	0.00712 ±0.00001	0.00696 ±0.00001	0.00699 ±0.00002	0.00702 ±0.00005	0.00709 ±0.00008	0.00709 ±0.00004
MRC Aero-Link	0.00735 ±0.00003	0.00707 ±0.00002	0.00658 ±0.00003	0.00668 ±0.00003	0.00680 ±0.00003	0.00689 ±0.00003	0.00744 ±0.00005	0.00697 ±0.00012
Simkins Egg	0.00688 ±0.00003	0.00670 ±0.00005	0.00661 ±0.00003	0.00664 ±0.00006	0.00685 ±0.00006	0.00719 ±0.00003	0.00759 ±0.00002	0.00692 ±0.00013
Magura RT8TT	0.00629 ±0.00005	0.00656 ±0.00003	0.00683 ±0.00003	0.00642 ±0.00006	0.00695 ±0.00007	0.00723 ±0.00009	0.00720 ±0.00003	0.00678 ±0.00014
TriRig Omega	0.00633 ±0.00001	0.00650 ±0.00006	0.00657 ±0.00003	0.00653 ±0.00011	0.00667 ±0.00004	0.00662 ±0.00008	0.00658 ±0.00005	0.00654 ±0.00004
Shimano Dura-Ace AX (BR-7300)	0.00656 ±0.00007	0.00621 ±0.00007	0.00576 ±0.00010	0.00601 ±0.00015	0.00599 ±0.00005	0.00648 ±0.00006	0.00645 ±0.00006	0.00621 ±0.00011
Hooker Aero SL	0.00602 ±0.00007	0.00591 ±0.00009	0.00580 ±0.00004	0.00585 ±0.00002	0.00595 ±0.00002	0.00616 ±0.00004	0.00627 ±0.00004	0.00599 ±0.00006
Fork only (no brake)	0.00507 ±0.00005	0.00522 ±0.00003	0.00528 ±0.00008	0.00565 ±0.00004	0.00524 ±0.00002	0.00529 ±0.00002	0.00525 ±0.00004	0.00528 ±0.00007

Values are mean ± standard error of the mean for n = 6-15 measurements per cell.

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