Quantifying Drag Contributions Of Dual Pivot Caliper Brakes Using R. Chung's Virtual Elevation Method

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Abstract

Wind tunnel testing is the standard test format for conducting drag testing on aircraft, automobiles, or even bicycles. This study evaluates the effectiveness of conducting semi-controlled experiments in-situ to resolve the drag force effects from relatively minor component changes on a bicycle using a power meter.

State of the Art

Conventional wind tunnel testing for cyclists often involves a rider who is positioned in a static position on a bike. This method only approximates flow around real-world cyclist for the following reasons:

a) Body position might be affected by road vibrations or jolts.
b) Body position might be affected by handling considerations.
c) Body position might be affected by slopes.
d) The cyclist might not be pedaling against a realistic load.
e) The wheels might not be rotating.
f) A stand is required to hold the cyclist and bike vertical and the stand might affect flow.

While wind tunnel testing might inform a rider as to their optimal position in ideal conditions, it might not translate exactly to their position in racing events. Even so, wind tunnel testing is generally considered the "gold standard" for aerodynamic testing of bicycle components and has been correlated to a relatively high degree to the power demands required in cycling on the road.

A more useful test would be able to resolve the contribution of aerodynamic drag for a cyclist riding on outdoor paved roads. Such calculations are routinely done with power meters. Standard protocols using power meters in conjunction with constant speed and level courses have been used to good effect. An alternative method proposed by Robert Chung allows for changes in speed and elevation. The ability to vary speed and elevation not only simplifies testing, it better simulates real-world conditions. http://anonymous.coward.free.fr/wattage/cda/indirect-cda.pdf
Note: Power meters have their drawbacks. The ability to resolve drag values over varying wind yaw angles is one advantage of wind tunnel testing over outdoor testing.

In the testing that follows, a single bicycle component, the front brake, was substituted for a difference brake. The Chung method was then applied to see if the replacement of a single component was detectable.

Test Environment

Test Course

The test path begins and ends on a hill. The path descends down a hill on a paved road, crosses a minor hill, and then ascends to a turnaround location on a larger hill. In this way the course is approximately a "W" shape as pictured in Fig. 1.

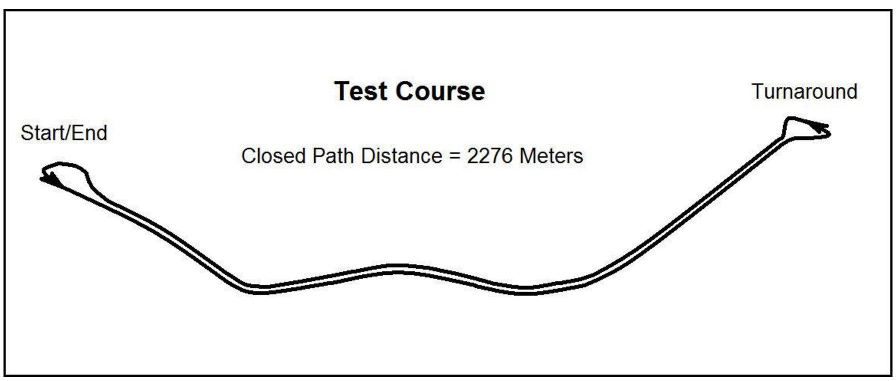

Figure 1 Three laps were completed for each run.

Conditions

The runs were conducted in August at a location in Southern California. Testing began at 06:55 and ended at 0:755 of the same morning. Environmental conditions such as wind, temperature, and air density are assumed to be static, a reasonable approximation given the duration of the testing.

Table 1

Static Conditions	
Total weight (lbs)	188

Temperature (F)	57
Altitude (ft)	50
Bar. Pres. (in Hg @ 0 ft)	29.98
Dry bulb temp- Dew point (F)	56
Transmission Loss (%)	0
Power Meter sample rate (s)	1.26
Crr	0.00470
Pressure (Pa)	101100
Vapor pressure (Pa)	1529
Dry Pressure (Pa)	99571
Density (kg/m^3)	1.220
Power altitude factor	0.999

Control Equipment

In order to see the if the VE Method can resolve small differences, all of the equipment (excepting the front brake) were identical for all runs. The test bike was a Cervelo P2K. The power meter used was a PowerTap Pro (wired). Likewise, the rider attempted to hold the same position for all runs while wearing all the same aerodynamic accoutrements.

Equipment Difference

The two brakes that were used are pictured below. The Cervelo OEM Mach 2 front brake pictured in Figure 2 a) is sculpted to reduce drag. However, the Mach 2 has the same basic design for all-around performance as many other commercially available caliper brakes. The Simkins Designs Egg Brake pictured in Fig. b) is specifically designed to minimize overall drag. Note, the Simkins Design Egg Brake version used in this testing was a prototype and not available commercially.

Figure 2 Side view of a) Cervelo Mach 2 brake, b) Simkins Designs Egg Brake.

Figure 3 Front view of a) Cervelo Mach 2 brake, b) Simkins Designs Egg Brake.

Results

A coefficient for rolling resistance had been determined previously for the rider and bike, Cdp = 0.00470. All analysis that follows assumes this constant.

Two runs were performed using the Mach 2 brake. The corrected virtual elevation plots for the first run is given as follows.

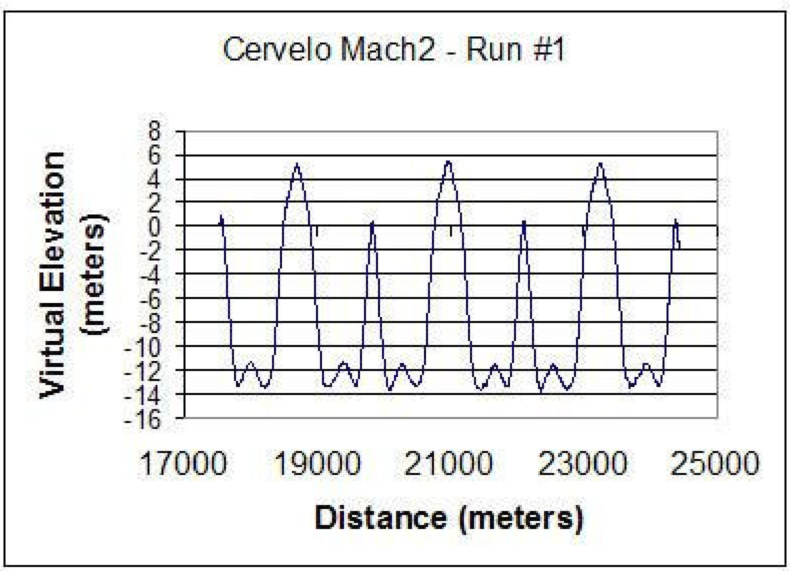

Figure 4 Graph corrected with CdA = 0.2155

The second run using the Mach 2 brake is given below. Note the non-periodic minimum virtual elevations for lap 2. This was due to a car entering the course at the middle (a side street) and coming towards the rider at the start of each of the 3 laps. The test rider reported some turbulent flow in the car's wake. Accordingly, the CdA was slightly higher and the VE plot was more variable than the first run.

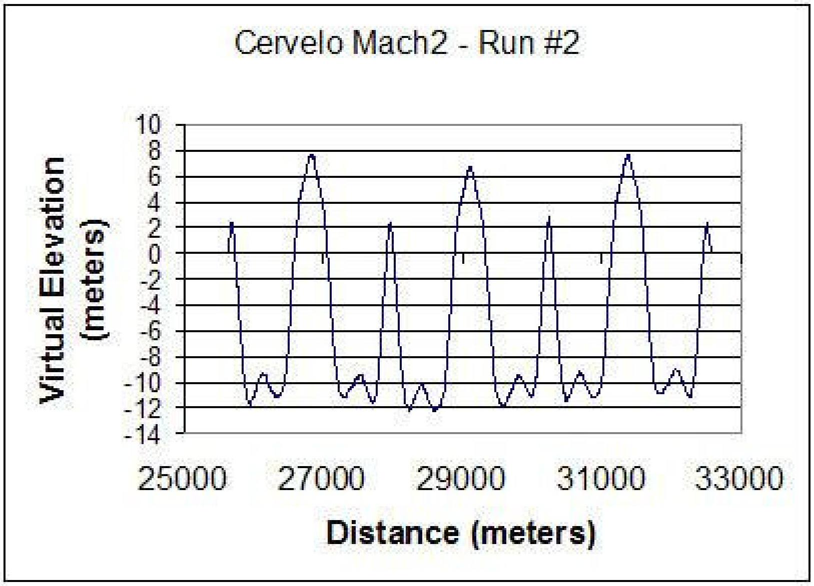

Figure 5 Graph corrected with CdA = 0.2170

The Egg Brake was attached to the test bike and the following data were collected.

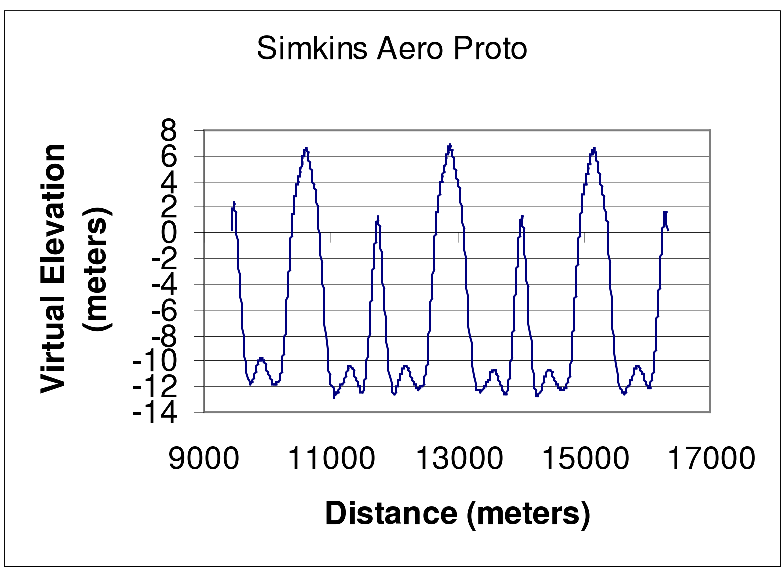

Figure 6 Graph corrected with CdA = 0.2130

Summary of Results

CdA coefficients were estimated using a visual interpretation of the virtual elevation plots. Per R. Chung's Method the correct CdA is determined by adjusting the CdA variable until the plot has a "level profile". The CdA coefficients summarized as follows were determined using this technique.

Table 2

Data Set	Front Brake	CdA
1	Mach 2 – Run 1	0.2155
2	Mach 2 – Run 2	0.2170
3	Egg – Run 1	0.2130

Assuming that the test rider were to perform a time trial on flat ground, with zero wind, the same air density, and at constant speed, the power output would be:

$$P = C_{rr}*m*g*v+1/2*C_{dA}*\rho*v^3$$

Where P = Power in Watts
C_{rr} = Coefficient of rolling resistance = 0.00470
m = Rider + bike mass = 85.3 Kg
g = Gravitational Constant = 9.81 m/s^2
ρ = Air Density = 1.228 kg/m^3
v = Speed = 28 mph = 12.52 m/s

The power difference between the Mach II and the Egg front brake is:

$$\Delta P = P_C - P_S = 1/2*\rho*v^3*(C_{dA(C)}- C_{dA(S)}) = \mathbf{3.0\ Watts}$$

Challenging the Results

A natural question that arises given this data is why the Mach 2 data would change so much between run 1 and 2. In fact, the difference between the two Mach 2 runs is almost as big as the difference between the better of the two Mach 2 runs and the Egg Brake. More specifically, the aforementioned analysis does not speak to the variation contribution due to test repeatability.

Quantifying Test Variation

In a perfect virtual elevation plot all of the local maximum and minimum elevations would be identical. More specifically, a small hill in the middle of the course should show up in the virtual elevation plot as having the same elevation each time it is crossed during a lap. Looking at the following figure, A1, A2, and A3, should have the same value. However, unknown perturbations such as road imperfections, air currents, or pressure gradients, will all contribute some variation that is not accounted for by the Chung Method assumptions. This is evident by varying magnitudes in the peaks. Additionally, if the CdA is poorly chosen the virtual elevation plot will have a slope, thus causing the variation to increase.

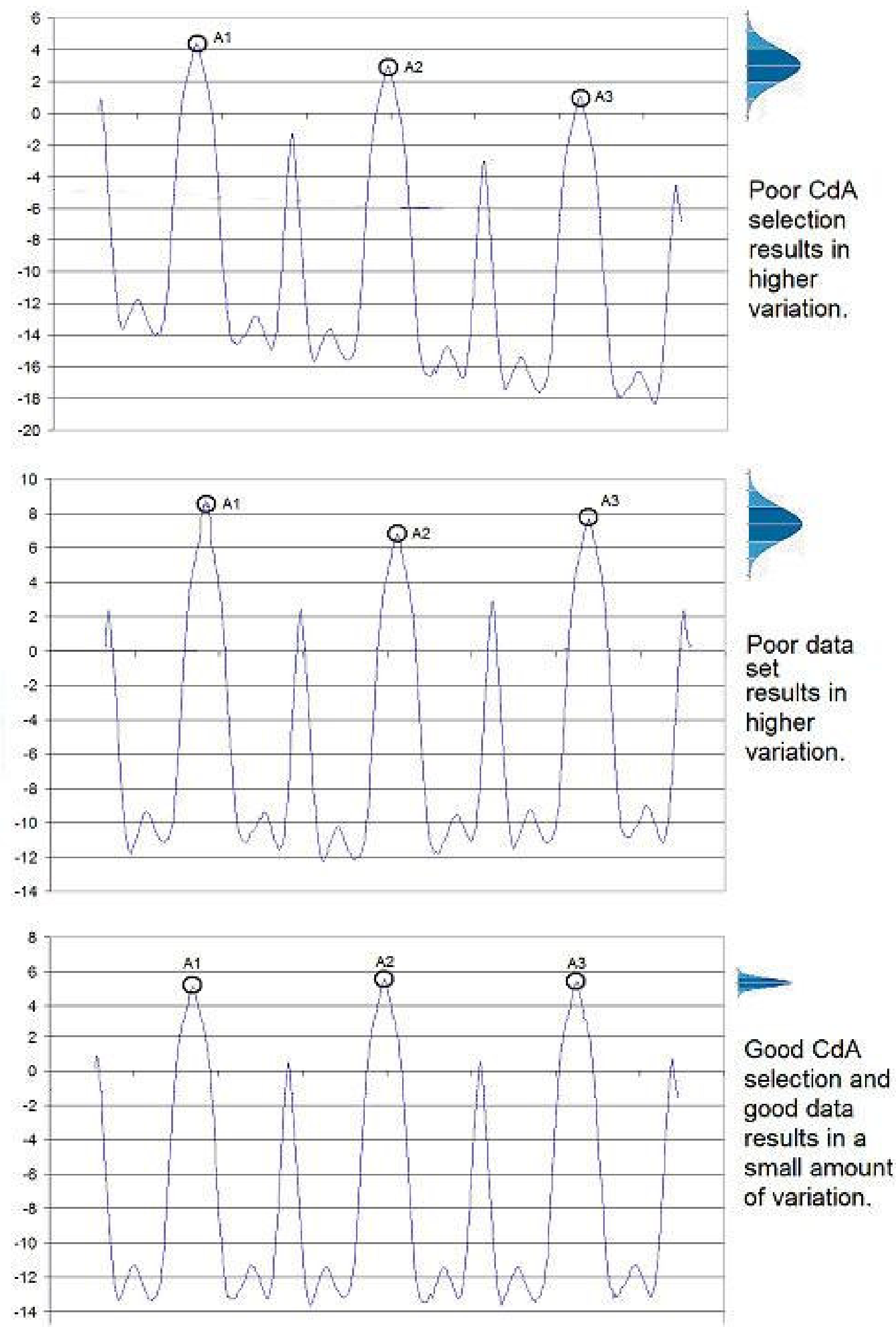

Figure 7

The CdA can be chosen with reasonable accuracy by visual inspection. In the preferred plot the peaks and valleys are roughly horizontal. However, a quantifiably justifiable CdA is obtained by calculating variation for each CdA selection. Of course, the best CdA choice will have the lowest possible variation.

Rather than calculate variation for only a single group of elevations, a more accurate approach would include more data points at multiple elevations. Variation was determined for each plot in the following way. Maximum and minimum elevations were determined. Each elevation was grouped into A, B, C, and D. For each elevation point the mean group elevation was subtracted and an overall standard deviation was calculated for the entire data set as follows:

$$\sigma=\{[(A1-\mu_A-\mu)^2+(A2-\mu_A-\mu)^2\ A3-\mu_A-\mu)^2\ A1-\mu_A-\mu)^2+(B1-\mu_B-\mu)^2+\ldots + (D3-\mu_D-\mu)^2\ ]/(N_A+N_B+N_C+N_D)\}^{1/2}$$

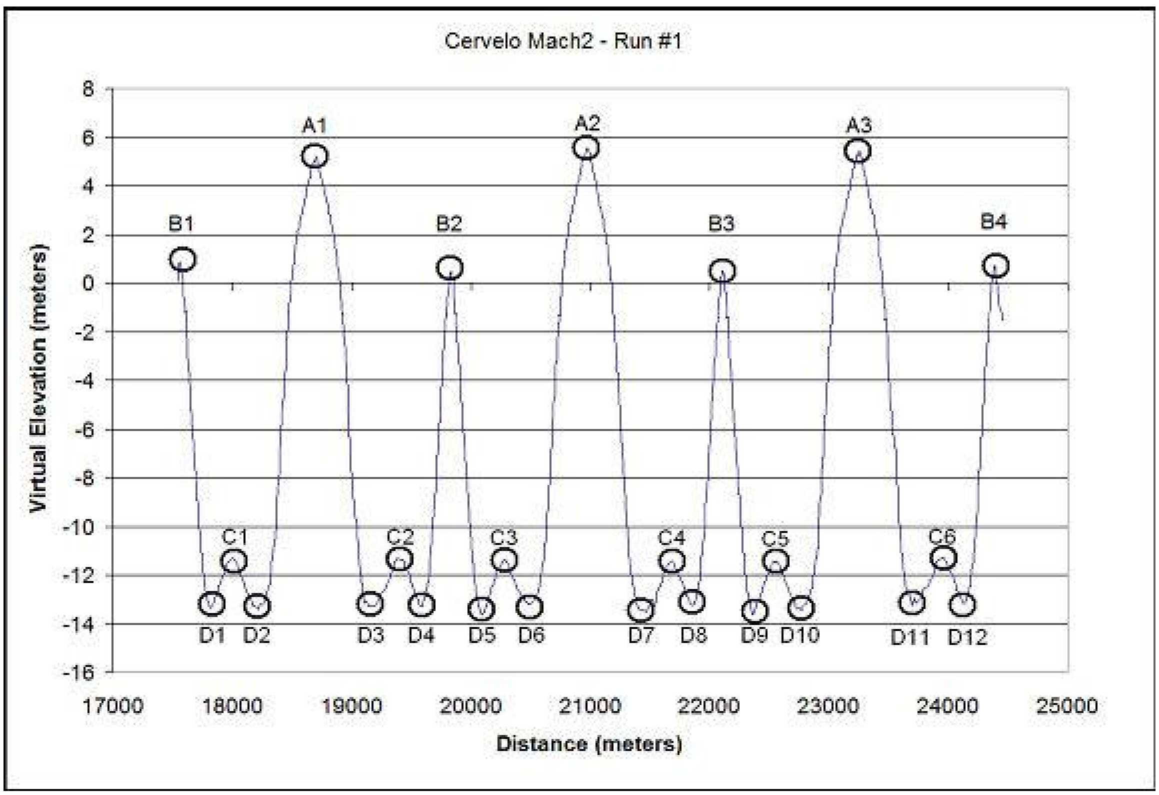

Figure 8

The optimal CdA coefficient is obtainable by zeroing in on the lowest corresponding variation, SD_{min}. Within rounding, the optimal CdA are depicted in the following figure. Comparing columns 3 and 4 shows that the selection of a CdA through visual inspection compares well with selecting a CdA by finding the lowest possible variation.

Table 3

Data Set	Front Brake	Visual Inspection CdA	Lowest SD CdA	Lowest Variation (SD_{min})
1	Mach 2 – Run 1	0.2155	0.2152	0.1375
2	Mach 2 – Run 2	0.2170	0.2182	0.4046
3	Egg – Run 1	0.2130	0.2125	0.3135

Resolving Differences

With a CdA having the lowest variation in hand, worst CdA^+ or CdA^- guesses can be made. Since the CdA with the lowest variation, SD_{min}, by definition has some variation; it is possible that the true value of the coefficient is higher or lower and that this it is being masked by variation in the test method. While there is no way to eliminate such a source of uncertainty outside of using better testing controls, it is possible to establish a confidence interval by studying the grand mean elevations of different CdA guesses. The "grand mean" elevation is interpreted here to including all maximum and minimum points for all elevations of a given run. Note, if CdA^+ represents a coefficient that was too high, the graph will slope downward. This will cause the grand average elevation will be lower, and vice-a-versa for CdA^-.

By definition, let μ_{CdA} represent the grand mean elevation for the CdA having the lowest variation, SD_{min}. Let μ_{CdA+} be the grand mean elevation for a CdA^+ guess that was higher than CdA, i.e. too high. If CdA^+ results in a μ_{CdA+} that is 2 SD_{min} form μ_{CdA}, then we can say that there is a (0.5)*95% likelihood that the true coefficient is between CdA and CdA^+. The converse is true for μ_{CdA-} and CdA^-. In this way, we can say with 95% confidence that $CdA^- <$ True Drag Coefficient $< CdA^+$. This concept is pictured as follows.

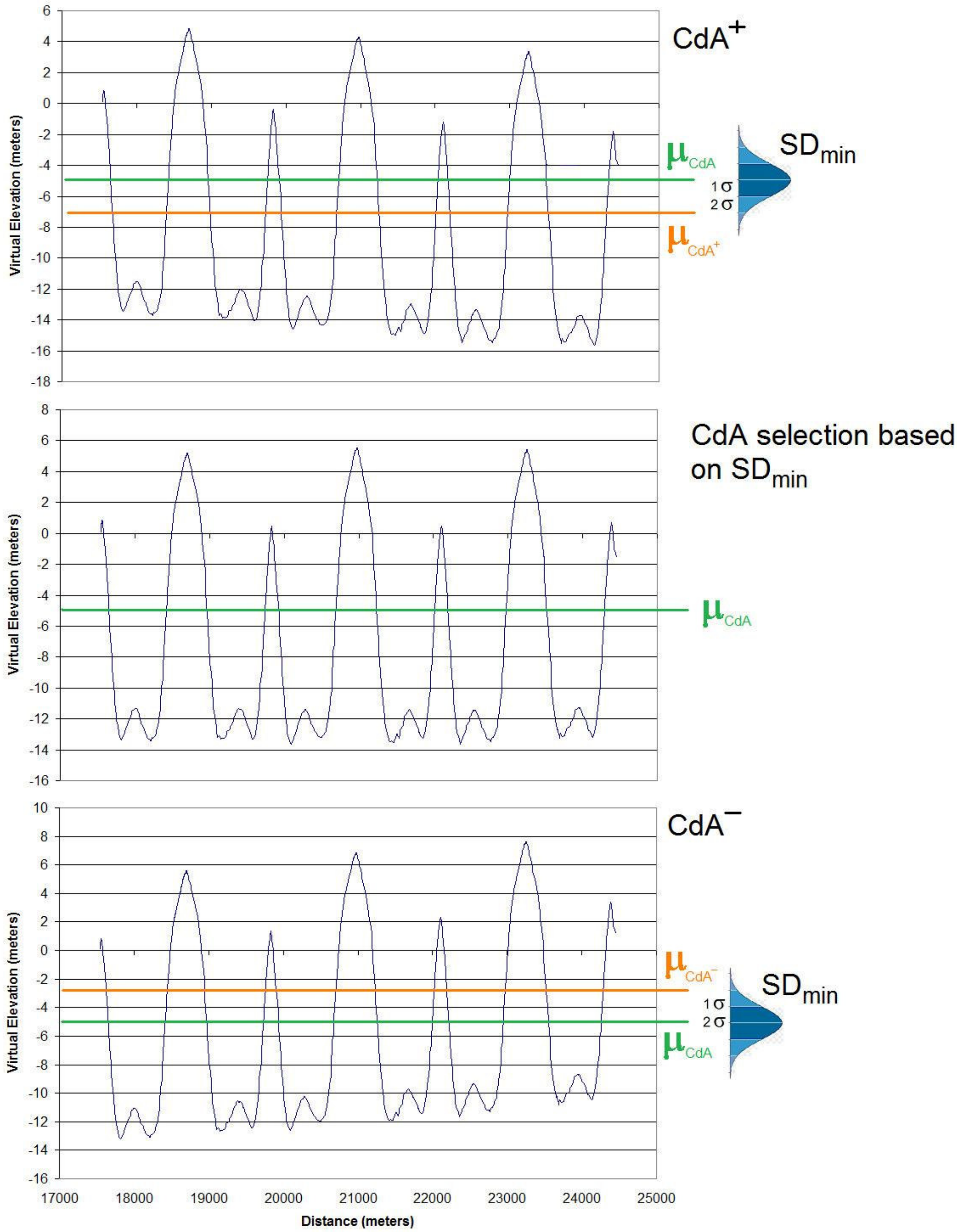
CdA+
Virtual Elevation (meters)
μCdA
μCdA+
SDmin
1σ
2σ
CdA selection based on SDmin
μCdA
CdA−
μCdA−
SDmin
1σ
2σ
μCdA
Distance (meters)

Figure 9

Using the aforementioned technique for calculating CdA ranges and confidence interval, the following data summary was obtained. Notice that data set 2 has the highest variation. Recall that cars had passed the rider for this run. It appears that a perturbation as subtle as a car driving past can introduce enough variation that it can obscure component differences. Likewise, it appears that the car slightly exaggerated the CdA for Run 2 of the Mach II. Also note that while the Simkins Egg Brake does appear to have a lower drag coefficient, test variation must be reduced to validate this claim with 95% confidence.

Table 4

Data Set	Front Brake	CdA	CdA Variation (SD_{min})	95% Confidence Interval
1	Mach II – Run 1	0.2152	0.1375	0.2142 < CdA < 0.2162
2	Mach II – Run 2	0.2182	0.4046	0.2152 < CA < 0.2212
3	Egg – Run 1	0.2125	0.3135	0.2102 < CdA < 0.2149

Conclusions

Like all testing, the Chung VE Method's precision is highly dependent on the circumstances of the testing. The investigator who conducted this study was well versed in the method and the location was carefully selected. Investigators using the Chung Method to evaluate rider position changes or equipment differences are well advised to consider test variation prior to making definitive conclusions.