Quantifying the Effect of Streamlining on Bicycles

Nickolas Hein ME599 Autumn Quarter 2000

Abstract

In this study performance of a streamlined vs. an unfaired bicycle were compared on hilly terrain with varying hill heights and various riding strategies. The resultant speed and energy to complete a hill cycle is compared. The full fairing was shown to provide a substantial advantage in all cases analyzed, even on long hill climbs. It is expected that application of power during riding can be optimized on the streamlined vehicle to provide the same speed with less effort. An effort to come up with a strategy for applying power was unsuccessful in the time available, however the intermediate results are presented.

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Introduction

Concerns about the environment and traffic congestion have resulted in more people taking to the roads under their own power on bicycles. However, the bicycle designs that are available do not provide year-round transportation for someone who wishes to abandon their car completely and in all types of weather. Here in the Pacific Northwest where there the conditions are usually no worse than light rain and cool weather a full-fairing would extend the riding season to most of the year. However, many riders object to the idea of a complete enclosure on the basis that the extra weight would make it more difficult to get up hills. Others rationalize that fairings are only of interest for speed record attempts. This rider has had experience to the contrary and wished to present a systematic way to demonstrate the savings in time and effort that are possible with a full fairing.

A few partial fairings for bikes are available today. They can be purchased easily, are made to mount on most recumbents and results in an astonishing performance improvement. Although it covers only the front 25% of the bike it cuts drag by half, resulting in a speed improvement of 20%. The reason for the popularity of this fairing is its relatively low price, low weight and the fact that it is available on test-ride bikes where a prospective buyer can feel the advantage first hand. Full fairings have been available commercially in the past but have not met with financial success – usually for reasons unrelated to performance. It was the goal of this report to show that the performance of full fairings can make them worth the weight and expense.

In an earlier report, the theoretical background and equations for this analysis were presented. Analysis was presented which showed that under ideal conditions with periodic hills and no coasting or braking, an increase in streamlining of a vehicle always resulted in a faster average speed on a complete hill cycle, even though the streamlined vehicle was always heavier and would be expected to go up the hill more slowly. In fact, the fairing (even a partial fairing) increased the speed under all conditions so the weight never resulted in a decrease in speed on any part of the hill. The present study will introduce the effects of coasting and braking to determine if the same is true under more realistic conditions. In these cases the energy expended by the rider will also be considered, because even if a more streamlined bike takes longer to get somewhere it will still have an advantage for some riders if it takes less effort to do so.

Test Vehicles for Comparison

The test vehicles used for this study are hypothetical designs intended to represent the unfaired and fully-faired cases from the previous study. The trends for partial fairings can be inferred from the previous study. A summary of the complete characteristics of both vehicles is presented below. A picture of what two such vehicles might look like is presented in the figure. Please note that although the pictures show a real and existing vehicle, the numbers are only representative of such a vehicle and do not represent measured characteristics.

Figure 1. Representative Vehicle without and with full fairing.[1]

Characteristics	Vehicle 1: Unfaired	Vehicle 2: Streamliner
Rolling Coeff.	.006	.006
Mech. Efficiency	.95	.95
Rider Power (W)	200	200
Rider mass (kg)	70	70
Frontal Area (m^2)	.6	.6
Drag Area (m^2)	.48	.072
Mass (kg)	15	30
P/W (m/s)	0.2399	0.2023
WD-10	28	223
Steady Speed (m/s)	8	13.6

Table 1. Characteristics of Example Vehicle without and with full fairing.

[1] Streamlined racing bike built and owned by Kevin Berls of Sunbury OH. Photos used with permission.

Test Setup

The differential equations for a vehicle operating on hilly terrain were derived in the earlier report, although this time they were implemented in MATLAB code (instead of a C program). A steady level-ground speed was calculated by trimming the vehicles until all accelerations were zero. Then the performance of the 2 example vehicles was compared by simulating rides over idealized (sine-wave) hills with a maximum slope of 5%. The equation for slope of the hills was derived in the earlier report. Height was determined by integrating slope over distance. The maximum height of the hills was varied because it was assumed that longer climbing times on larger hills would give the lighter, unfaired bike an advantage. The 5% slope was chosen because in the earlier report this was the slope at which the faired vehicle had the least advantage on large hills. The following test cases were run:

1) Rider pedalling at all times (to duplicate the results of the previous report)
2) Rider coasts (stops applying power) any time speed is above 15 m/s
3) Rider brakes (prevents speed from increasing) any time speed is above 20 m/s
4) Rider starts from rest at the bottom of a hill (Worst case for heavy bike).

For each test run the elapsed time, average speed and total work were recorded for comparison.

Results

The following plots represent the phase plots of time history runs over hilly terrain. The hills have a maximum slope of 5% and vary in height (10m, 20, 40, 60, 80, 100m). In the first series of tests it is assumed that the rider pedals at all times throughout the run. Each of the plot rings is in the plane of its height. The red rings are projections of the first and last blue rings onto the floor of the plot, to provide a depth cue when reading the plots. The plot permits a general assesment of the vehicle's efficiency from a quick glance at the width of the acceleration range and the speed range. The better the streamlining, the wider the range of acceleration, the faster the average speed and the wider the speed range. With no wind resistance and no rider input a vehicle's maximum acceleration (plotted in g's) would be nearly equal to the maximum slope of the hill.

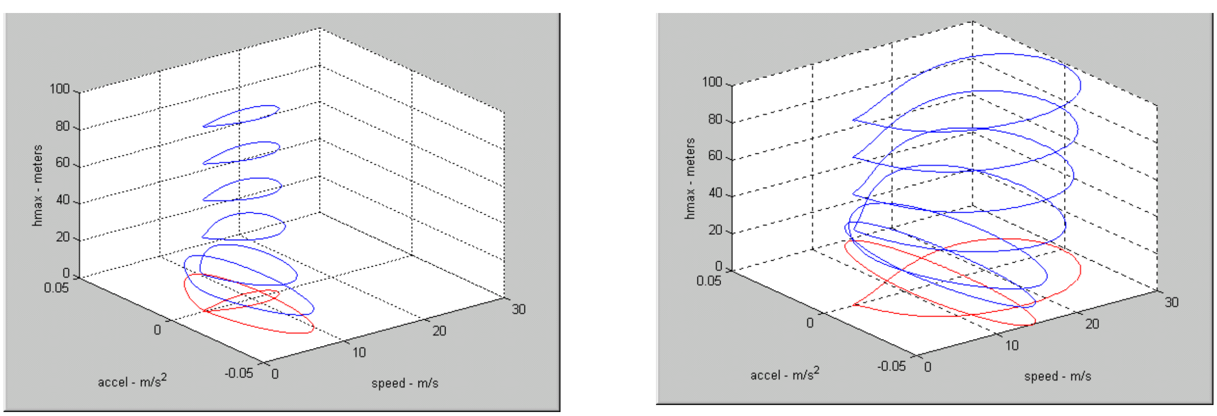

Figure 2. Phase Plots for Unfaired and Fully-Faired Vehicles - Constant Pedalling (Case 1)

On shallow hills the speed varies little, being limited by the fact that the potential energy from the hill doesn't add or take much from the kinetic energy of the vehicle. As the hills get larger the speed variation gets larger as the potential energy is greater. On an unfaired vehicle, however, most of this additional energy is lost to wind resistance. A sharp point appears on the left end of the plots as hill size increases. This is evidence of the point where momentum runs out when going up a hill and the climbing speed is dependent only on the Power-to-Weight ratio.

	Average Speed		Elapsed Time		Work Expended	
Height	Streamlined m/s	Unfaired m/s	Streamlined sec	Unfaired sec	Streamlined KWH	Unfaired KWH
10	13.6	7.3	46.2	86.1	0.01	0.03
20	12.6	7.0	100.1	178.8	0.03	0.06
40	10.8	6.9	232.8	362.8	0.08	0.12
60	9.9	6.9	379.2	546	0.13	0.18
80	9.5	6.9	529.6	728	0.18	0.24
100	9.2	6.9	681	911	0.23	0.30

Table 2. Comparison for Unfaired and Fully-Faired Configurations (Case 1)

From the plots it is clear that the streamlined vehicle has strikingly different performance. In all cases the average speed is higher, the acceleration range is greater and the speed range is much greater. The streamlined bike reaches maximum acceleration of +- .05 (because of pedalling) on shallow hills. Much of the acceleration range is retained on the larger hills. The speed range on larger hills is much greater than with the unfaired bike because the potential energy from the hill is retained instead of being dissipated by wind resistance. The average speed, elapsed time and total work are shown in Table 2.

However, the top speeds are somewhat unrealistic because they reflect the rider pedalling at all times. In actual operation the rider would either coast or brake at high speeds. Coasting was simulated by cutting out the rider power whenever the speed exceeded 15 m/s, the phase plot for this case is shown in Figure 3. Because the unfaired vehicle never reached a speed of 15 m/s it's performance was unaffected.

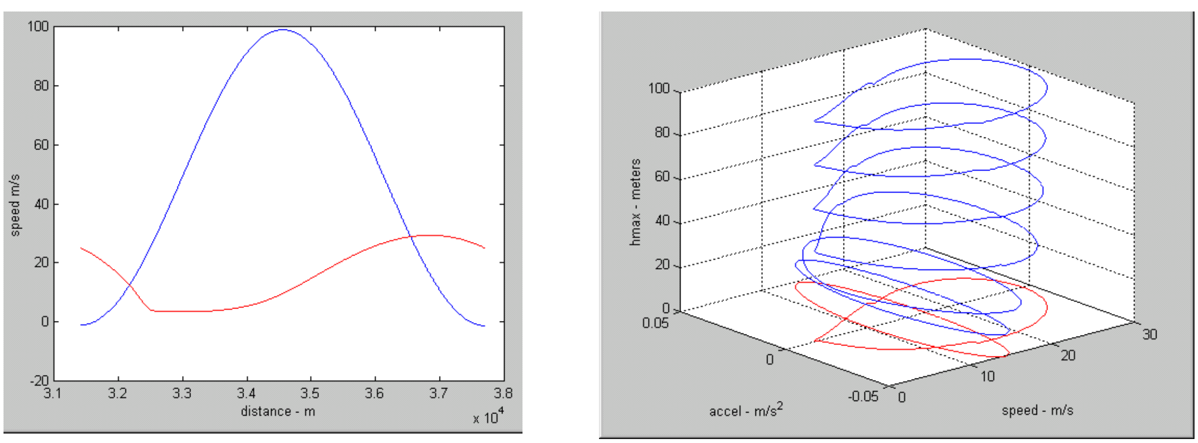

Figure 3. Streamlined Vehicle with Coasting above 15 m/s. (Case 2)

The effect of coasting is barely noticeable as a kink in the phase plot at 15 m/s on both the accelerating and deccelerating sides of the cycle. As is shown in Table 3 the average speed is slightly less, the elapsed time longer, but the work expended was also less.

Height	V_{avg}	Time	Energy KWh
10	13.5	46	0.01
20	12.5	100	0.03
40	10.7	234	0.08
60	9.9	382	0.13
80	9.4	534	0.18
100	9.2	686	0.22

Table 3. Performance of the Fully-Faired Configuration with Coasting (Case 2)

The effects of braking were simulated next by freezing (stopping integration of) the velocity when it exceeded 20 m/s. The time-history and phase plots for this case is shown in Figure 4. On the phase plot all of the cycle is cut off completely above 20 m/s. The straight line extending left of the cycle is an artifact of the freeze, in that the acceleration is still calculated even though it is not integrated to get velocity. Table 4 summarizes the the average speed, time and energy for this case.

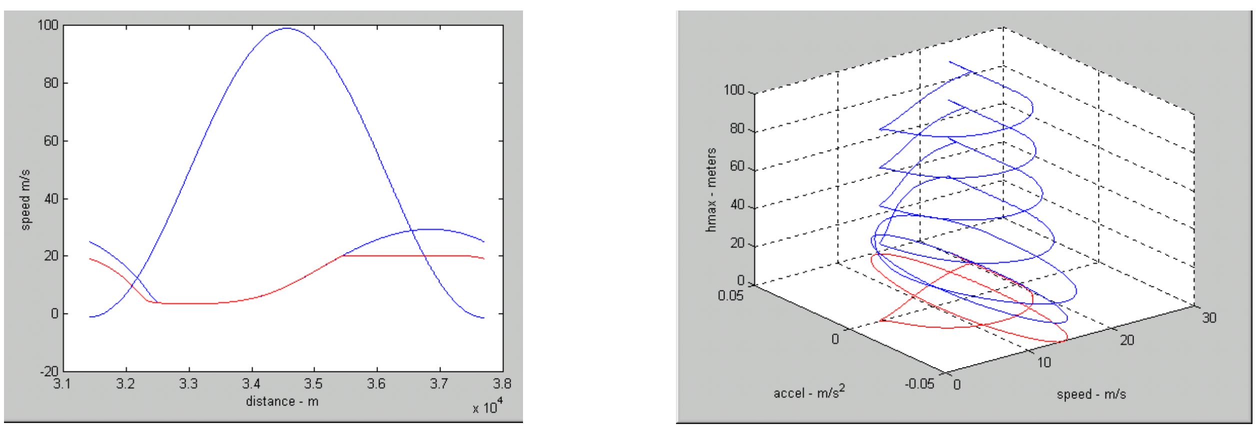

Figure 4. Time-history and Phase Plot for Streamlined Vehicle with Braking above 20 m/s. (Case 3)

Height	Vavg	Time	Energy KWh
10	13.2	46	0.01
20	12.0	102	0.03
40	9.2	264	0.09
60	8.6	425	0.14
80	8.3	585	0.19
100	8.1	743	0.25

Table 4. Performance of the Fully-Faired Configuration with Braking (Case 3)

The final test case involved starting both vehicles from rest at the bottom of a hill and comparing the average speed, time and work required to complete a single hill. The results are shown in Table 5 and Figure 5. The surprising result was that the streamlined vehicle required less effort to complete the hill for all hill sizes tested. Figure 5 shows why this is the case. Although the streamlined bike is heavier and goes slower on the steepest part of the hill, the distance over which it goes slower is relatively short (approximately 1500 m). On all other parts of the hill the streamlined bike is so much faster that the total elapsed time is less. Even more surprising ly, the advantage increased on larger hills. It is unknown whether partial fairings would not give as great an advantage. However, this appears to be a good scenario to use to compare benefits of partial fairings, since it represents a good "worst-case".

	Average Speed		Elapsed Time		Work Expended	
Height	Streamlined m/s	Unfaired m/s	Streamlined sec	Unfaired sec	Streamlined KWH	Unfaired KWH
10	6.3	6.1	100	103	0.006	0.006
20	6.9	6.4	183	196	0.010	0.011
40	7.4	6.6	341	382	0.019	0.021
60	7.6	6.6	494	568	0.028	0.032
80	7.8	6.7	645	753	0.036	0.042
100	7.9	6.7	794	939	0.044	0.052

Table 5. Performance of the Unfaired and Streamlined Configuration Starting from Rest. (Case 4)

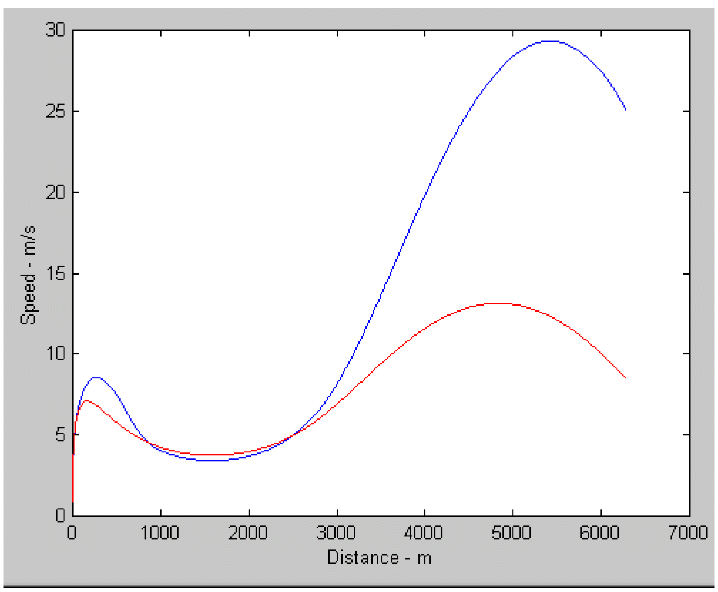

Figure 5. Streamlined (blue) and unfaired (red) vehicles starting uphill from rest. (Case 4)

Analysis

In the cases where coasting was used on the high-speed portions of the hill (Case 2) it was shown that the rider of the streamlined bike didn't lose much speed with this strategy. It is reasonable to expect, then, that if the rider input power was applied sinusoidally but out of phase with the terrain profile (pedaling at the slower speeds and coasting at the higher speeds) the average speed could be maintained with much less effort. It should be possible to determine the phase delay of power application that would provide the highest average speed with the least effort. An unsuccessful attempt was made to find a simple method to predict this phase shift. It will be described here to provide a starting point for future study of the subject.

In the earlier report the static governing differential equation was derived:

$$\mathbf{n_x = x''/g \;=\; \eta*(P/W)\,/x' - (\mu + \gamma) - [.5*\rho \;/\; (W/CdA)] * (x')^2}$$

where **x''** represents acceleration and **x'** is velocity. This equation is highly non-linear and doesn't lend itself to an exact solution. Several efforts were made to make it look like a linear differential equation. Re-arranging (and neglecting rolling resistance and mechanical efficiency losses) and replacing **a** for acceleration and **V** for velocity:

$$\mathbf{a - g *(P/W)\,/V + [.5*\rho\, g \,/\, (W/CdA)] * V^2 = \gamma\, g}$$

Assuming: $\gamma\mathbf{a} = \mathbf{h''}$, $\gamma\mathbf{V} = \mathbf{h'}$ and $\mathbf{mV^2/R = mh''}$ yields:

$$\mathbf{h''/\gamma - \; g *(P/W) \,/\, h' + [.5*\rho\, g *\gamma * d\gamma/dx * (W/CdA)] * h'' = \gamma\, g}$$

$$\mathbf{h''[1.0 + .5*\rho\, g *\gamma * d\gamma/dx * (W/CdA)] - [\gamma^2 g(P/W)] \;/\; h' = \gamma^2 g}$$

This retains a first derivative term in the denominator that makes it difficult to solve. In addition γ, although it is not explicitly time-dependent, has a secondary time dependence throug x (distance). The derivation was not pursued further.

Summary

A summary of the average speeds for all cases is presented below, showing the difference between fully-faired and unfaired configurations under the conditions analyzed. In spite of the additional weight of a fairing, the streamlined configuration was faster in all cases.

Height	Case 1	Constant	Pedalling	Case 2	Coasting	
m	Streamlined	Unfaired	% diff	Streamlined	Unfaired	% diff
10	13.6	7.3	86%	13.5	7.3	85%
20	12.6	7	80%	12.5	7	79%
40	10.8	6.9	57%	10.7	6.9	55%
60	9.9	6.9	43%	9.9	6.9	43%
80	9.5	6.9	38%	9.4	6.9	36%
100	9.2	6.9	33%	9.2	6.9	33%

Table 6a. Average Speed Summary for Case 1 and Case 2.

Height	Case 3	Braking		Case 4	Starting at	Rest
m	Streamlined	Unfaired	% diff	Streamlined	Unfaired	% diff
10	13.2	7.3	81%	6.3	6.1	3%
20	12.0	7	72%	6.9	6.4	8%
40	9.2	6.9	34%	7.4	6.6	12%
60	8.6	6.9	24%	7.6	6.6	15%
80	8.3	6.9	20%	7.8	6.7	16%
100	8.1	6.9	18%	7.9	6.7	18%

Table 6b. Average Speed Summary for Case 3 and Case 4.

It is not certain whether the same will be true for partially faired configurations, but it is likely since they have less weight at the same time the provide more drag.
The advantage for the full fairing is substantial in the first 3 cases. It is much less when starting from rest at the bottom of a hill (Case 4), which was expected. However, the advantage increases as the hills get larger. This result was unexpected, but can be explained by the fact that the starting portion is a smaller fraction of the hill as the hill gets larger. On the tallest hill the advantage for the streamlined configuration is the same as for the braking case.

It should be noted that the idealized sin-wave hills used for this analysis have a constant distribution of slope, which is unlikely to be matched exactly in the real world. Actual hills might be expected to have nearly-constant grade over their entire length and that would put the heavier bike at a disadvantage during climbing. The author has surveyed one route with hills of varying sizes and found that the steepest portions are generally short, and for that route the conclusions of this study will hold. However, if a bike is to be used on a specific route where these assumptions may not hold, a survey should be done before deciding whether or not (or how much) to streamline the design.

Conclusions

This study has proven that a well-designed fairing will be faster on hills in all of the cases analyzed, under the assumptions made. It is expected that application of power during riding can be optimized to provide the greatest speed with the least effort. An effort to come up with a strategy for applying power was unsuccessful in the time available, however it is anticipated that applying power sinusoidally and with a phase relative to the phase of the hill would be optimum. Future study might undertake to arrive at the method for determining this phase angle.