An Experimental Study of Cycling Shoes Impact on Time Trial Races

by

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Abstract

The main purpose of this thesis work was to investigate how different cycling shoes drag would affect the outcome of a time trial race. The difference in drag between the different shoes was expected to be small and therefore the accuracy of the measurements needed to be sufficiently high. One racer shoe and one MTB shoe was tested together with a shoe cover. As a reference four robust models , denoted club feet were manufactured and tested. A wind tunnel at HIG (University of Gävle) was used to perform the tests due to it's large test section area and the newly developed method of measuring. The difference in drag between the shoes showed to be measurable and also an estimated time saving for elite time trial cyclists could be calculated.

Contents

CHAPTER 1

Introduction

1.1. Introduction

In individual time trial (TT) cycling (which is a part of e.g. Tour de France) the riders start with 60 seconds interval and therefore can not take advantage of laying in the wake of another rider, hence the aerodynamic becomes very important. Commonly the track is about 40-50 km and the riders need about 1 hour to travel this length. Often in these races the winner has a margin of just a couple of seconds or even hundredths of a second. The most famous example of the importance of aerodynamic in TT came in 1989 (Tour de france) when the American Greg Lemond was 50 seconds behind Laurent Fignon from France. There was only one day remaining of the 20 days, $\sim$ 3500 km had been traveled and it was just a 25 km long TT left. Laurent Fignon came to start with, at the time, normal cycling apparel, no helmet, conventional 'cowhorn' bars and also had the benefit of starting behind Lemond and therefore an advantage of getting Lemonds times. Lemond on the other had was equipped with aerohelmet, aerobars, and a rear disc wheel. Lemond gained 58 seconds on Fignon and won Tour de France 8 seconds before Fignon (**?**). Did Lemond won because he was more aerodynamic? In **?** they compares the 'cowhorn' bars used by Fignon to aerobars used by Lemond and finds that the one biking with aerobars will save 1 - 2 minutes on a 40 km long time trial at 48 km/h (30 mph), which very well complies with the outcome of 1989's Tour de France.

In 1982 Chester Kyle and others started to work on a complete aerodynamic configuration for the US Olympic Cycling Team for the 1984 Olympics in Los Angeles. They developed new bikes, suits and helmets, this was the first time anyone made a complete rider and bike aerodynamically optimized solution (**?**). The bikes built were called 'funny bikes' because of their different and odd design. The front wheel were smaller than the rear wheel for two reasons, first the rider get a more aerodynamic position, secondly the rider will get benefits in team time trial due to the fact that he can lay closer behind the other riders and hence receive less air resistance. The US Cycling team ended up with two gold medals, two silvers and a bronze, these were the first medals for 72 years for USA.

However, one can start wondering why the bikes still looks pretty much the same for as a bike for 100 years ago. If Chester Kyle and his Olympic team would have been free to develop a completely new human powered vehicle without any restrictions it would not look like a bicycle. Union Cycliste International (UCI) are the governing organ in the cycling sport, they are the ones that have decided how a bicycle should look to be allowed to compete in international and regional races. There are many structural rules about the design, but also some important rules when it comes to aerodynamic. Rainer Pivit summarize the aerodynamic rules with *"UCI regulations specify a conventional seating position and also forbid any aerodynamic accessories. Not forbidden, however, is the aerodynamic arrangement of functionally necessary components"* (**?**). This means that it is forbidden to add aerodynamic accessories that are not necessary for structural stability. For example it is not allowed to cover a spoked wheel with a plastic sheet to enhance the aerodynamic performance. But if the plastic sheet (rather some composite material) is needed to carry the structural load it is allowed.

Since the strict regulations according to the bike design has stopped the development of the bicycle frames the riders and their teams are now looking for new ways to enhance the aerodynamic performance without breaking the rules. In this report it will be analyzed if there are any difference in aerodynamic drag between different shoes and if this drag reduction would outcome in any relevant time reduction in a 40 km time trial race. According to **?** the shoes that are used today are made for high comfort rather than for high aerodynamic performance. The shoes often has large straps, holes for air intake and a thick sole for rigidity. Most of these aerodynamic disadvantages can be avoided with a shoe cover that makes the surface of the shoe more streamlined. To investigate the difference in drag between different shoes a wind tunnel will be used. The optimal wind tunnel test would probably be to use a rider that could move and pedal exactly the same each test with different shoes and measure the difference of wind resistance. However such rider does not exist and therefore some simplifications were made. The tests will be static tests (the leg will not be pedaling), the crank arm will not be connected to a bicycle frame. Due to these simplifications it will be possible to measure, like expected, very small force differences that would not have been possible to measure in a dynamic test.

How the experimental setup became can be seen in the following chapter. Chapter 3 will then go through the different test objects (Racer shoes, MTB shoes, and club feet) and explain the differences between these. In chapter 4 some analytical calculations of the boundary layer will be done to validate that it does not affect the model. A rough analytical estimation of the model load will also be done to make sure that the load cell used is sufficient. Data processing is treated in Chapter 5, and the result is shown in Chapter 6. In Chapter 7 and 8 the Conclusions and Discussions are.

CHAPTER 2

Experimental Setup

The wind tunnel used in the experiment could be used thanks to Mats Sandberg at Gävle University (HIG).The tunnel is normally used for environmental studies due to its ability to create an atmospheric boundary layer. Due to the tunnels great dimensions (length 11 m, hight 1.5 m and width 3 m) large models of cities can be mounted and investigated with good results.

2.1. Wind Tunnel

The wind tunnel used is a closed circuit low speed wind tunnel with a cross section of 3×1.5 m^2 (width $\times$ height) and an 11 m long test section. The tunnel has a maximum speed of 22 m/s which is enough to simulate bicycle speeds. The wind is generated from one electric engine that through hydralics drives two fans.

2.2. Measuring Equipment

To measure the forces acting on the cycling shoe a load cell was used, Figure 2.2. The load cell was chosen to withstand forces up to 2 kg based on analytical estimations of the aerodynamic drag of the test objects. The load cell was delivered from Vetek and is of the type single point in aluminum. It is classified according to the highest accuracy standard (C3) which means that the measuring range is divided into 3000 parts, this gives an accuracy of (2000/3000) 0.66 grams or 0.0065 N. The load cell was then connected via an amplifier to an A/D data acquisition board. The analog signal was sampled by a computer via the software LabView. The signal was sampled for 60 seconds in order to average out any possible vibration of the model.

2.3. Calibration

Since the setup rig was new and the accuracy of the load cell needed to be determined the load cell was tested with different weights (100, 200 and 500 g) that could represent the actual load on the shoe during tests. The load cell was very accurate for all weight and it was concluded that the load cell voltage output increased linearly with the load. As seen in Figure 2.3 the weight was mounted in a wire that via a wheel with bearings was connected

FIGURE 2.1. Picture from the rear end of the wind tunnel.

to the crank arm. To ensure that the load cell was working properly it was calibrated between every change of angle.

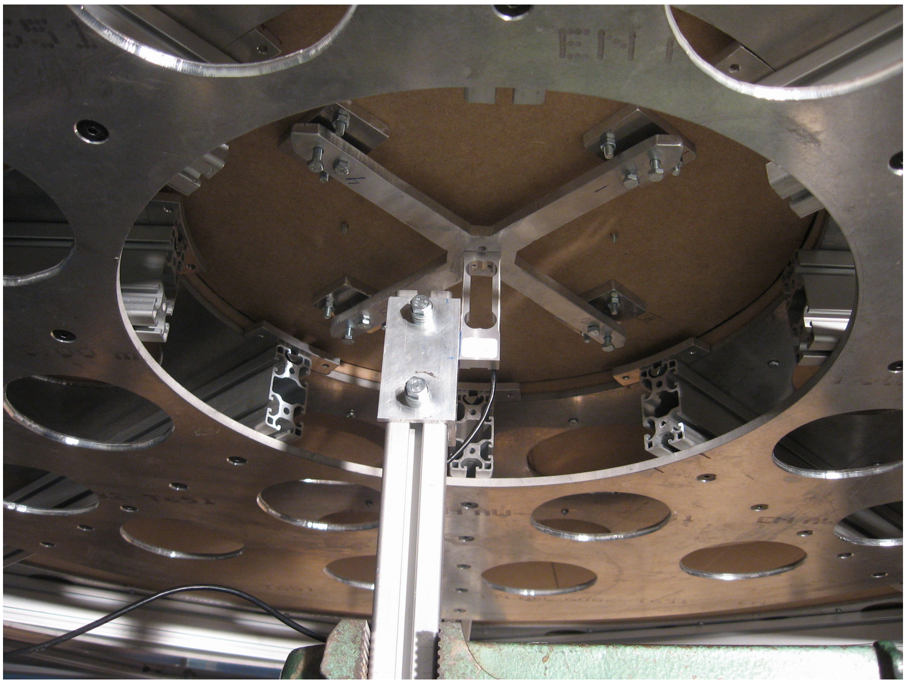

Figure 2.2. Picture from under the test section showing how the load cell was mounted to the test rig plate.

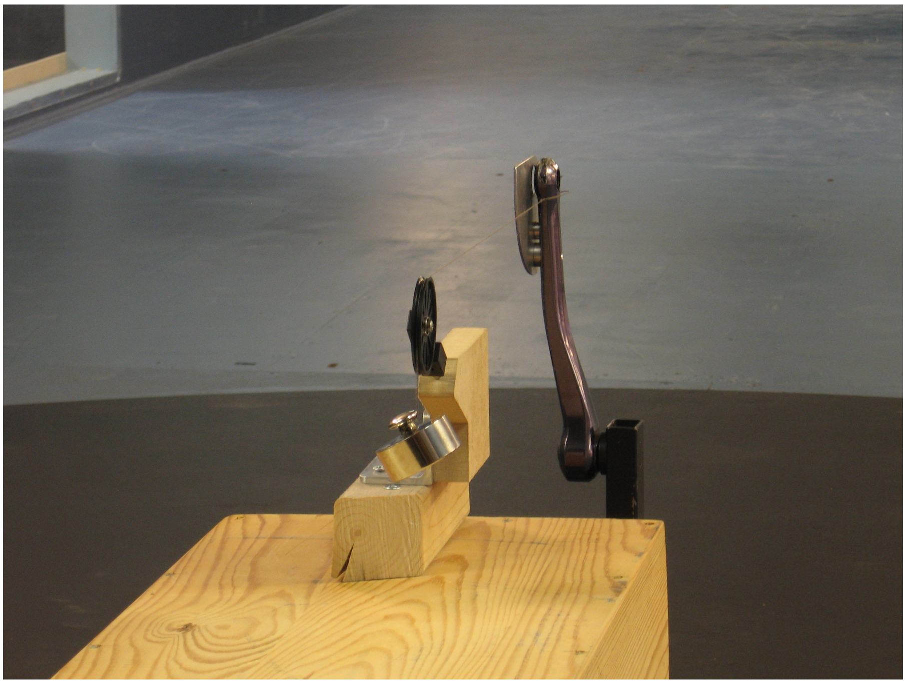

FIGURE 2.3. Picture of the calibration, setup with 200 g weight.

CHAPTER 3

Test Objects

Today it exists many type of shoes for cycling, and for every shoe type there are several pedal systems that can be used to mount the shoe to the pedal with. Two normal shoes (Mountainbike (MTB) and racer shoes) and a couple of test objects called club feet will be tested. Also the effect of shoe cover will be investigated. To make the simulations better and also cover the interaction between the leg and the shoe a plastic leg is mounted to the shoes. The Club feet will use a cylinder as a 'leg'. The test objects consist of four Club feet, one racer shoe, one MTB shoe and a shoe cover that fits both the MTB shoe and the racer shoe. This gives a total number of eight different models, all shoe combinations can be seen in Figure 3.3. Below follows a brief description of each one of the test objects.

3.1. Racer Cycling Shoe With LOOK Pedal System

The racer shoe has a very slim shape and is manufactured by Cannondale which is a well known company in the bicycle industry. Like most other racer shoes this one uses the LOOK (company name) system (Figure 3.2) for mounting the shoe to the pedal. On the LOOK system the cleats are precipitated. The pedal is larger than the corresponding MTB pedal, but somewhat more streamlined. On the top of the shoe there are 2 Velcro buckles and 1 pump buckle (similar to the one on ski boots). These buckles and especially the pump buckle makes the upper side of the cycling shoe pretty rough. The underside of the shoe is made of plastic which gives maximum stability and hence large power transfer to the pedal and drive line, on the other hand the plastic makes the shoe almost impossible to walk with.

3.2. MTB Cycling Shoe With SPD (Shimano Pedaling Dynamics) Pedal System

The MTB shoe is the Shimano M 72 which is a very common shoe for mountain biking. It uses Shimano's SPD pedal system that has recessed cleats on the shoe which makes pedestrian easier. The pedal which can be seen in Figure 3.2 are a bit smaller than the LOOK pedal but is more rectangular shaped. On the upper side of the shoe there are 2 Velcro buckles for tightening the shoe to the foot. The Underside of the shoe is made of rubber and has a tread pattern

FIGURE 3.1. Picture showing the cylinder mounted to the club foot and the plastic leg in the racer shoe.

FIGURE 3.2. MTB pedal (SPD system) to the left and racer pedal (LOOK system) to the right.

for improved grip on roots and rocks. This rubber pattern makes the underside of the shoe rougher than the racer shoe. There is also a plastic core inside the shoe which gives stability when pedaling, it is however not as stiff as the racing shoe.

3.3. Shoe Cover

Shoe covers are a thin piece of fabric, often made of Nylon and polyester, that is worn over the shoe to cover buckles and other protruding parts. The idea is to create a smoother and more even surface with the purpose to lower the wind resistance. Shoe covers are today used by every elite racer cyclist.

FIGURE 3.3. MTB shoe, Racer shoe and the shoe cover.

3.4. Club Feet

When investigating aerodynamics on advanced shapes like bicycle shoes it can be good to look at some simpler models first. Therefore four different robust models, denoted Club feet, were manufactured. They all have the same length, width and height but have different geometrical shapes (Figure 3.4). The width of the club feet was set to 100 mm. Club foot C is shaped as an ellipse using Equation 3.1 , where a was set to the half shoe length (semi-major axis) and b was set to the half shoe height (semi-minor axis). Club foot D is a half ellipse but with the same length and height as Club foot C. Club foot B is a half ellipse and a half rectangle and clubfoot A is shaped as a regular rectangle.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{3.1}$$

All Club feet were made in Styrofoam because of the ease to work with the material and that it is light. The Styrofoam was formed to the desired shapes with a band saw, thereafter treated with black water based varnish for enhanced surface hardness. A cylinder was also added in the rear end of the foot to simulate the lower part of the leg (see Figure 3.1) To mount the Club feet to the pedal the MTB system SPD was used.

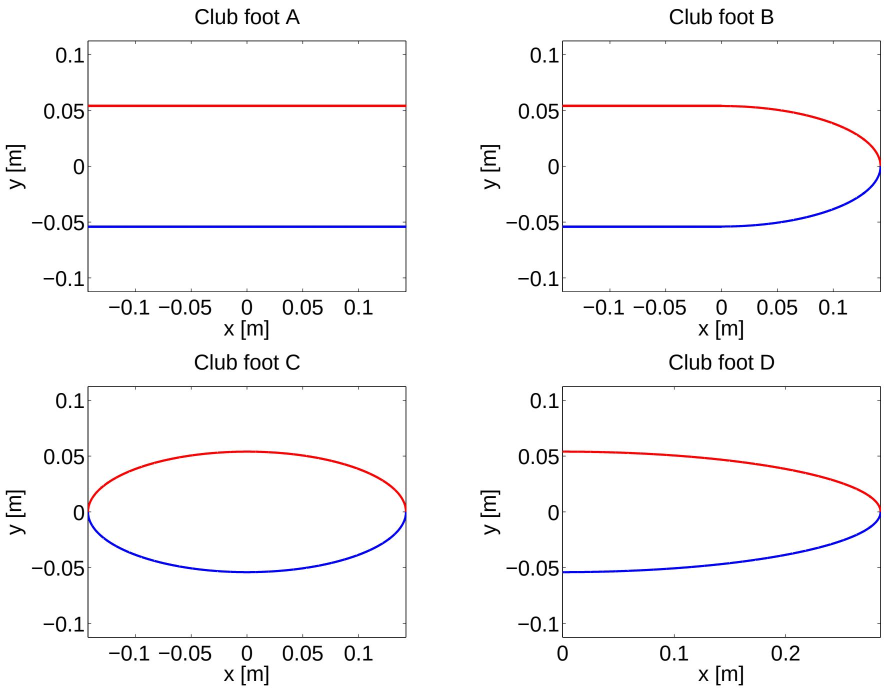

FIGURE 3.4. Club feet A, B, C & D

CHAPTER 4

Preparation of Wind Tunnel Test

4.1. Analytical Estimation of Model Load

To measure the load on the models in the wind tunnel a load cell is used. In order to choose the appropriate tolerance of the cell an analytical estimation of the maximum load on the model is necessary. The drag was calculated by using Equation 4.1

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S} \tag{4.1}$$

where C_D is the drag coefficient, $\frac{1}{2}\rho V^2$ the dynamic pressure and S the reference area of the model. Since the drag coefficient for the whole model is unknown one has to divide the model into several parts with known drag coefficients. The "leg" of the club feet is a cylinder with a length to width ratio of 6.4 and for a typical Reynolds number of $\sim 10^4$ gives a drag coefficient of 0.75 (**?**). An expected result is that the rectangular Club foot A is the one that produces most drag, hence it is a good idea to base the drag estimation on this type and use the corresponding known drag coefficient for such shape. A cube typically has a drag coefficient of ∼1 with the same Reynolds number as above **?**. Adding this to Equation 4.1 gives

$$D_{clubfoot} = C_{Drec}\frac{1}{2}\rho V^2 S_{rec} + C_{Dleg}\frac{1}{2}\rho V^2 S_{leg}, \tag{4.2}$$

where the frontal area S_{rec} and S_{leg} can be calculated from Figure 4.1 . In Figure 4.2 the drag calculated has been plotted for possible bicycle speeds, one can see that the load cell is not restrictive.

4.2. Boundary Layer

Since the air is moving and not the model in a wind tunnel there will be a boundary layer near the floor. The boundary layer is created because of the viscosity of the fluid that makes it stick to the ground. Actually the air molecules are not still but the mean velocity component in the wind direction on the surface of the floor is zero. So if the setup with cycle shoe would be located in this boundary layer the velocity distribution around it would not be

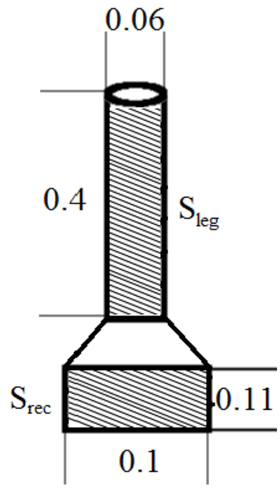

FIGURE 4.1. Sketch over Club foot, [m].

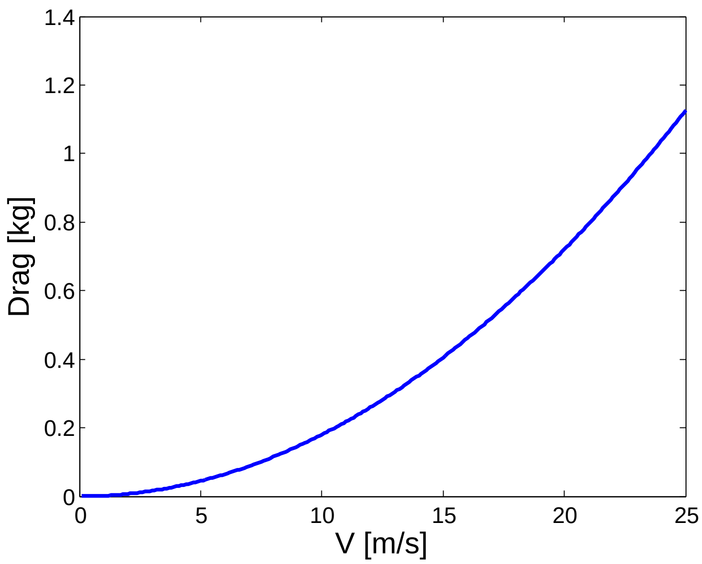

FIGURE 4.2. Analytical calculations on the drag of the model.

the same as if the shoe was on an actual road. However there are some standard methods that one could apply to avoid this effect. One is to have a moving belt under the test object so that the ground is moving at the same speed as the

V [m/s]	4	8	12	16
Re	3.0×10^6	6.0×10^6	9.0×10^6	1.2×10^7
δ [m]	0.21	0.18	0.17	0.16

TABLE 1. How Reynolds number and boundary layer thickness, δ varies at the end of the test section.

wind giving a zero speed difference. Unfortunately this method is not available in Gävle's wind tunnel. An easier method is to place the test object outside the boundary layer so the effect of it in this case can be neglected. To do this the thickness of the boundary layer needs to be estimated.

A turbulent boundary layer thickness on a flat plate can be estimated by using the following empirical relation **?**.

$$\delta = \frac{0.37x}{Re_x^{1/5}} \tag{4.3}$$

where x is the downstream extent of the boundary layer and Re_x is the Reynolds number based on the downstream distance. The relation above coincide well with experimental data in the range of $5 \times 10^5 < Re < 10^7$ **?**. The Reynolds number was calculated by using Equation 4.4

$$Re = \frac{\rho V x}{\mu} \tag{4.4}$$

where ρ is the density of air, V the speed of the wind, x the downstream distance and μ the dynamic viscosity of air. The downstream distance, x, corresponds to the inlet of the test section in the wind tunnel to the model which in this case is 11 m. In Table 1 one can see how Reynolds number and δ varies with the wind tunnel speed. At 16 m/s the Reynolds number is slightly above the permitted value for Relation 4.3. For the other speeds the equation is valid and δ seems to vary between 0.16 m and 0.21 m. From above estimation it can be stated that the cycle shoe needs to be placed at least 0.21 m above the test section surface to avoid boundary layer effects. In Figure 4.3 one can see how the boundary layer develops along the test section with a wind speed of 4 m/s in the tunnel.

4.3. Testing Scheme

The test objects consists of four Club feet, one racer shoe, one MTB shoe and a shoe cover that fits both the MTB shoe and the racer shoe. This gives a total number of eight different models. Each model needs to be tested in the range

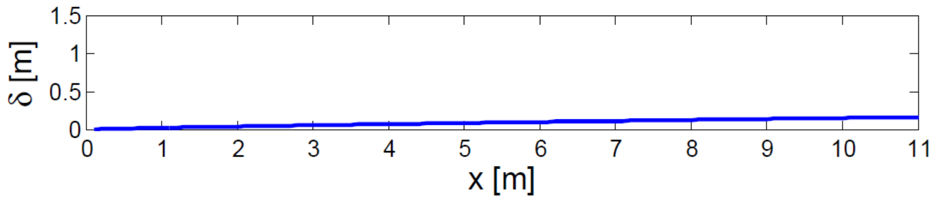

FIGURE 4.3. How thick the turbulent boundary layer is in proportion to the test section of the wind tunnel.

of normal (in this case elite) bicycle velocities to be able to see how the drag coefficient vary. The maximum speed in the wind tunnel is 22 m/s but can not be run for long time periods due to overheating problems. This speed is not an unrealistic bicycle speed but is considered relativity high. A maximum speed of 16 m/s was instead chosen. The minimum speed was selected to 4 m/s, this is a relatively low speed for a bicyclist but is still interesting to study for academical reasons. To be able to do all measurements within the rental time of the wind tunnel it was decided to do measurements on 4, 8, 12 and 16 m/s on each shoe.

Since a cycle shoe is not horizontally leveled during one revolution it is also of interest to change the pitch angle of the shoe to see how this effects the drag. By studying pictures on Elite cyclists it was decided to test four angles -10, 0, 15 and 30° where 0° is leveled pitch, negative sign means nose up and positive nose down. How the foot change angle during one revolution can be seen in Figure 4.4

FIGURE 4.4. Picture showing how the pitch angle of the shoe change during one revolution.

CHAPTER 5

Data Processing

5.1. Calculation of Frontal Area

To be able to calculate the drag coefficient one has to determine the measured objects frontal area. The frontal area is defined as the projected area of the body on the plane vertical to the direction of the flow (**?**). By photographing the object with a digital camera from long distance (to avoid perspective effects) one will have a picture of the frontal area. In a standard image processing program e.g. GIMP one can determine the number of pixels in a selected field. To transform number of pixels in to a frontal area in square metre one needs an object in the image with known length, in this case the crank arm was used as the reference length. The crank arm has a length of $Crank_m = 200$ mm (exterior dimensions) that in Figure 5.1 corresponds to $Crank_{px} = 348$ px. Number of pixels that the frontal area of the shoe in Figure 5.1 consists of are called $Area_{px}$. In Equation 5.1 a relation between the area of the shoe and the length of the crank arm is shown.

$$\frac{Area_m}{Area_{px}} = \left(\frac{Crank_m}{Crank_{px}}\right)^2 \tag{5.1}$$

By solving for $Area_m$ one can achive the frontal area in square metres. The frontal areas for each cycling shoe are listed in Table 1. One can see that each cycling shoe is smaller without shoe cover (SC) than with, for all angles. Another conclusion is that the racer shoe and MTB shoe are very similar when it comes to frontal area.

5.2. Dynamic Pressure

Since both the temperature and the atmospheric pressure vary during the test the density will also change. During the tests the temperature and the atmospheric pressure variations were noted so that the measurements could be normalized and hence accurately compared. The density can be calculated using the ideal gas law Equation 5.2

$$P = \rho RT \tag{5.2}$$

where P is the atmospheric pressure, R the specific gas constant for dry air, T the temperature in Kelvin and ρ the density. Both the atmospheric pressure and the ambient temperature were measured and consequently ρ could be

FIGURE 5.1. Picture of the frontal area on the racing cycling shoe.

Angle	S_{Racer}	$S_{RacerSC}$	S_{MTB}	S_{MTBSC}	S_{clubA}	S_{clubB}	S_{clubC}	S_{clubD}
-10°	0.0252	0.0261	0.0248	0.0253	0.0300	0.0296	0.0287	0.0232
0°	0.0271	0.0276	0.0266	0.0270	0.0295	0.0290	0.0290	0.0291
15°	0.0289	0.0299	0.0298	0.0299	0.0342	0.0320	0.0315	0.0289
30°	0.0313	0.0319	0.0320	0.0325	0.0381	0.0342	0.0332	0.0331

TABLE 1. Frontal area for different cycling shoes [m^2]

calculated. The dynamic pressure can now be calculated with according to

$$q = \frac{1}{2}\rho V^2 , \tag{5.3}$$

where V is the speed of the wind tunnel.

5.3. C_D Calculations

Since both the dynamic pressure q and the frontal area S have been calculated and the drag D has been measured the drag coefficient C_D can be calculated according to its definition,

$$C_D = \frac{D}{qS} . \tag{5.4}$$

There are two types of drag, pressure drag and skin friction drag, that can be written

$$C_{Dtot} = C_{Dp} + C_{Df} \tag{5.5}$$

where C_{Dp} are pressure induced drag and C_{Df} are friction drag caused by the viscosity of the fluid. For bluff bodies, like the one in the experiment, C_{Df} are relatively small compared to C_{Dp}.

CHAPTER 6

Results

The results from the measurements are presented in drag coefficient (C_D) and drag factor ($C_D \cdot S$), where S denote the frontal area of the model. Both are of interest when comparing aerodynamic performance. Since the area between the different shoe combinations differ it is important to also compare the drag factor to be able to make fair comparisons. If one is only interested in the shape of the shoe the drag coefficient is more important since it is normalized with the frontal area.

6.1. Club feet

The result of the Club feet measurements can be seen in Figure 6.1 there the drag coefficient has been plotted against the velocity for four different angles, each plot corresponds to an angle. Each shoe model will be referenced to as how they were named in Chapter 3. At $-10°$ model A has the highest C_D, model A has the second highest and models B and C are almost having the same value. In normal tests of reference figures they are tested at 0 degrees, hence the result at this angle will be a bit more like one might have expected. Model A definitely has the highest C_D while the rest of the models pretty much has the same result. Inclining the models $15°$ forward model C has the highest C_D while the rest of the shoes are having pretty much the same value for all speeds. At $30°$ model A has the lowest C_D and model C has the highest.

As mentioned before it is not necessarily so that the shoe with lowest drag coefficient has the lowest drag, due to the frontal area. In Figure 6.2 one can see the drag factor plotted against the velocity. Model A has the highest drag independent of angle.

6.2. Cycling shoes

In Figure 6.4 the drag coefficient for the two different cycling shoes with and without Shoe cover (SC) are shown. One can see that the drag coefficients for each shoe vary between the different angles tested. At $-10°$ the MTB shoe with shoe cover has the lowest drag coefficient independent of speed, the racer

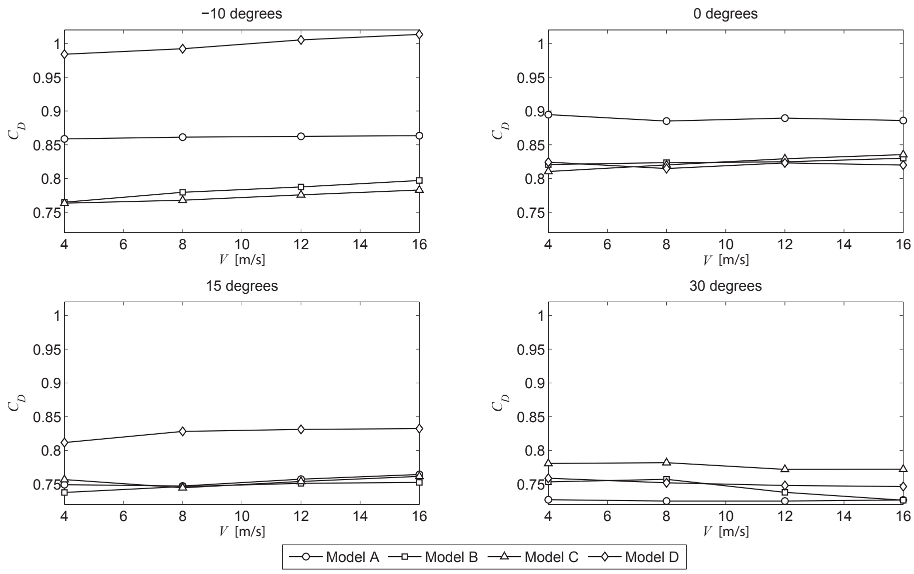

FIGURE 6.1. Figure showing the drag factor, $C_D \cdot S$, for the four club feet at different speeds. Four angles are shown, −10, 0, 15 and 30°, each plot is for a given angle.

shoe and the MTB shoe without shoe cover have the highest drag coefficient. At 0° the different shoe types results vary between the different speeds. The racing shoe with shoe cover is however performing best in almost all speeds. When inclining the shoe forward the results between the different shoe types differ more, perhaps because of the bigger frontal area that are facing the wind. In the two following angles the racer shoe with shoe cover performs a lot better than the other shoes, the shoe without shoe covers have higher drag coefficients.

In Figure 6.5 one can see the drag factor for each shoe typ plotted against the velocity for four different angels, each plot corresponds to one angle. As mentioned above the results in this plot tells us which shoe type that would have performed best in a race. Due to the difference in numbers between the different angles the vertical axis are not fixed, hence the comparison between different angles becomes more difficult but it is easier to compare different shoe types at the same angle. One can see that at −10° the MTB shoe with shoe cover has the lowest drag for all speed, the racer shoe with with shoe cover has the highest drag. At 0° it is not possible to say which shoe that has the lowest drag. At 15° the difference between the different shoes are easier to sort out and one can see that the racer shoe with shoe cover has the lowest drag. The racer shoe has lower drag than both the MTB shoe and the MTB shoe with

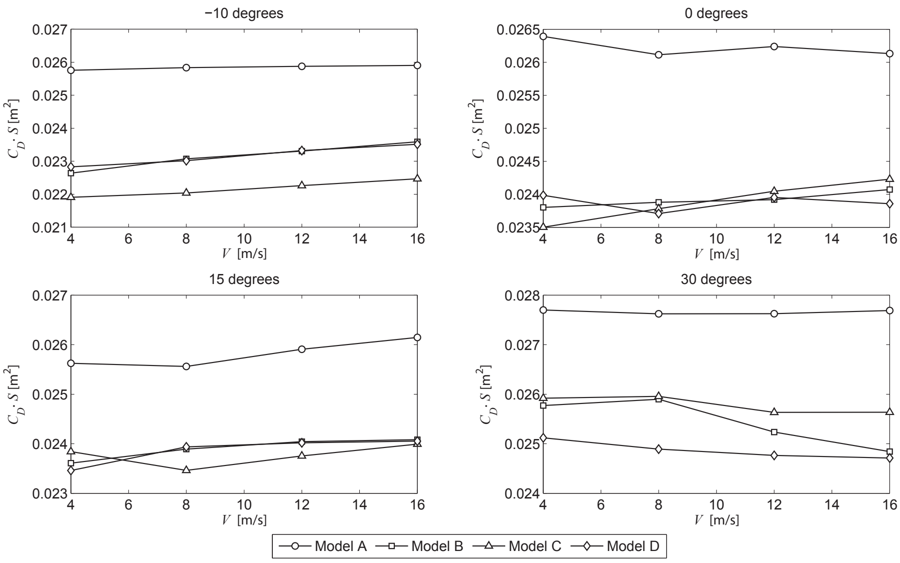

FIGURE 6.2. Figure showing the drag factor, $C_D \cdot S$, for the four club feet at different speeds. Four angles are shown, -10, 0, 15 and 30°, each plot is for a given angle

shoe cover, which almost has the same drag. At 30° the difference between the shoes are higher than at the other angles and again the racer shoe with shoe cover has the lowest drag. Overall the racer shoe with and without shoe cover has lower drag than the MTB shoes with or without shoecover. For the racing shoe the shoe cover seems to lover the drag at high angles (15 and 30°, but have the opposite effect on low angles. For the MTB shoes the effect of the shoe covers are not as high as on racer shoes.

A smoke visualization was also made (Figure 6.3) to see if there were any special flow patterns that could be studied. One can see that the flow behind the model are distorted like expected for a bluff body. It is however hard to see any vortices or other flow phenomenas.

In Figure 6.6 one can see how the drag coefficient for different angles vary with the speed for the MTB shoe SC and Racer shoe SC. The Racer shoe SC has the lowest drag coefficient at 30° for all velocities except 16 m/s where -10° has the least. The MTB shoe SC has the lowest drag coefficient at -10° for all velocities. One can also see that the differences in drag coefficient are larger for the MTB shoe SC than with the Racer shoe SC.

By instead letting the drag coefficient be a function of the pith angle ϕ (Figure 6.7 one can easier see patterns of how the drag coefficient vary with ϕ. For the Racer shoe SC the lines follows a clear trend with low drag coefficient at -10° and 30° and high drag coefficient there between. The MTB shoe SC plot in Figure 6.7 follows the same trend but with a more obvious peak at 15^{circ} .

Figure 6.8 shows the drag factor as a function of velocity for the different angles. One can see that there in both plots are pretty large difference between the drag factor dependent on which angle the model is mounted in. To see how big this difference is in percentage compared to the drag factor at 0° it was normalized with this drag factor according to Equation 6.1,

$$\frac{R(\phi, V) - R(0, V)}{R(0, V)} \tag{6.1}$$

where R is the drag factor dependent of pitch angle ϕ and wind speed V. In Figure 6.9 one can see the results ploted for the MTB shoe SC and Racer shoe SC. The MTB shoe SC is the one that is most sensitive to change in inclination and can have a drag reduction of up to 24 percent at 30° compared to the drag at 0°. The racer shoe SC has a drag reduction of up to 15 percent at the same angle. For both cases the drag reduction is largest at high velocities.

It was also investigated if one could see any clear difference in drag reduction by using shoe cover on the two different shoes. In Figure 6.10 one can see how much one can *Gain* by using Shoe covers, where *Gain* is defined by,

$$Gain = \frac{R(\phi, V) - R_{sc}(\phi, V)}{R(\phi, V)} \tag{6.2}$$

where R is the drag factor for the shoes without SC and R_{sc} the drag factor with SC. For -10° it is not beneficial to use shoe covers on the Racer shoe but for the MTB shoe it can be beneficial. At 0° it can be beneficial to use SC depending on the speed, for high speed on both the MTB shoe and Racer shoe the air resistance can be reduced. For higher angles of inclination the gain becomes larger for the Racer shoe, one can also see that there is a speed dependence, where higher speed gives larger gain. The speed dependence is also noticeable when looking at the MTB shoe.

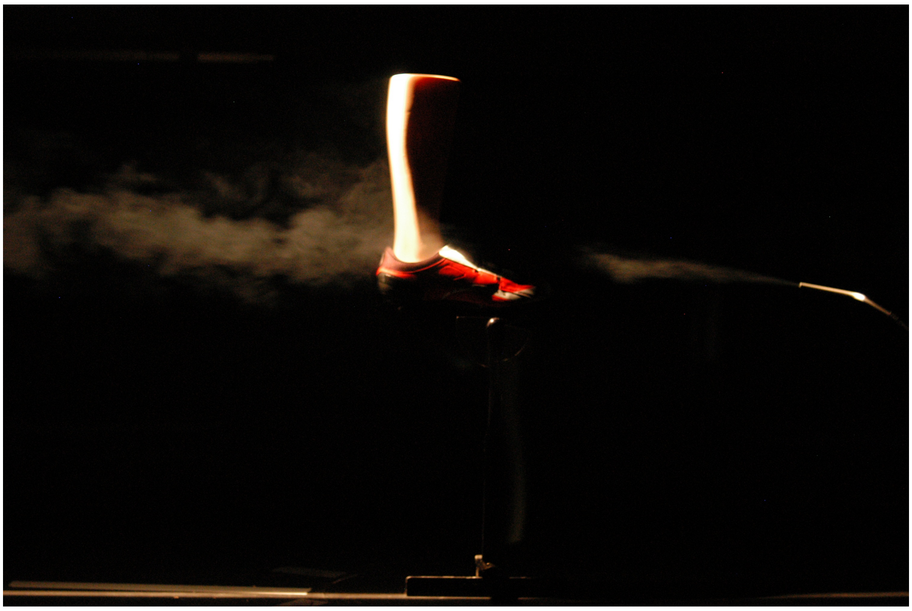

FIGURE 6.3. Racer shoe during smoke visualization.

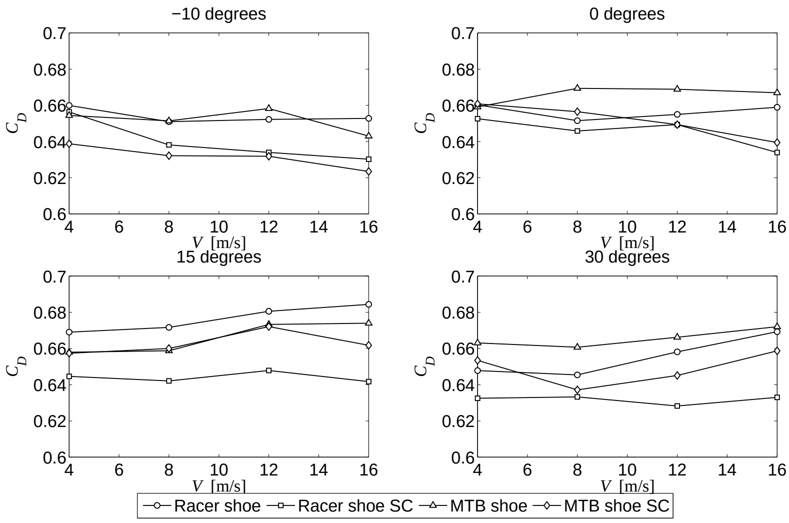

FIGURE 6.4. Figure showing the drag coefficient, C_D, for the two cycling shoes with and without Shoe covers (SC) at different speeds. Four angles are shown, -10, 0, 15 and 30°, each plot is for a given angle.

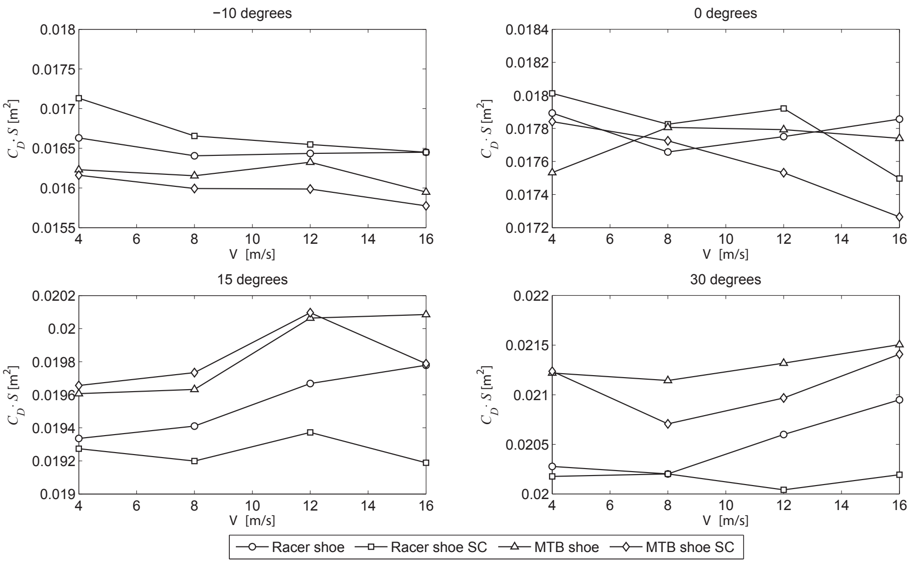

FIGURE 6.5. Figure showing the drag factor, $C_D \cdot S$, for the two cycling shoes with and without Shoe covers (SC) at different speeds. Four angles are shown, -10, 0, 15 and 30°, each plot is for a given angle

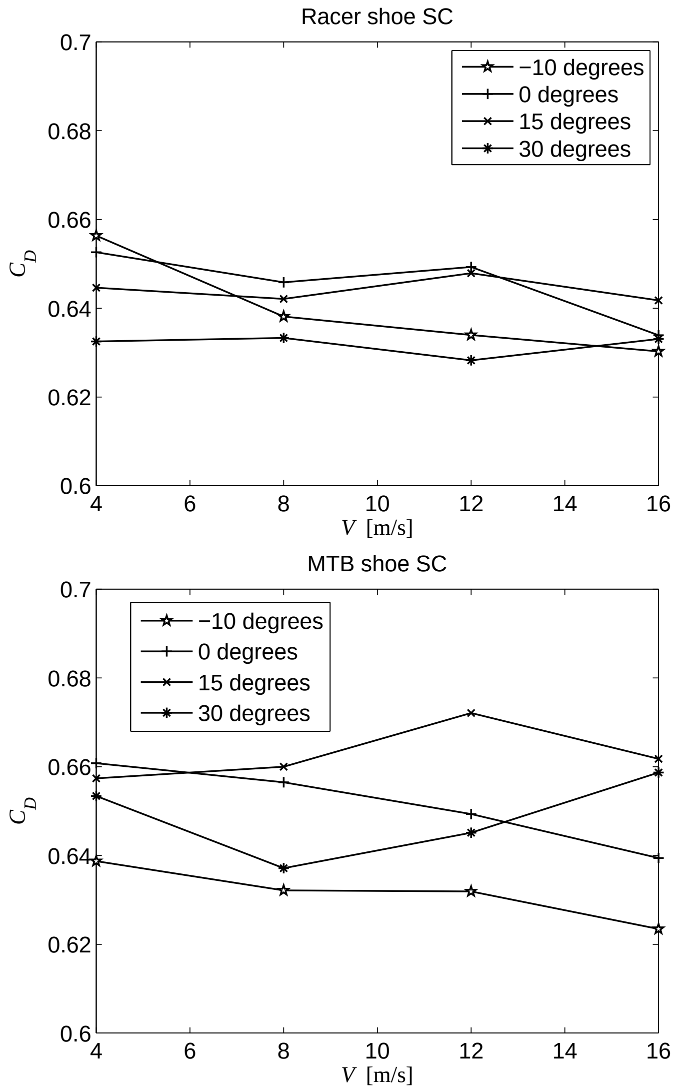

FIGURE 6.6. Figure showing C_D for Racer and MTB shoe SC as a function of speed for different angles.

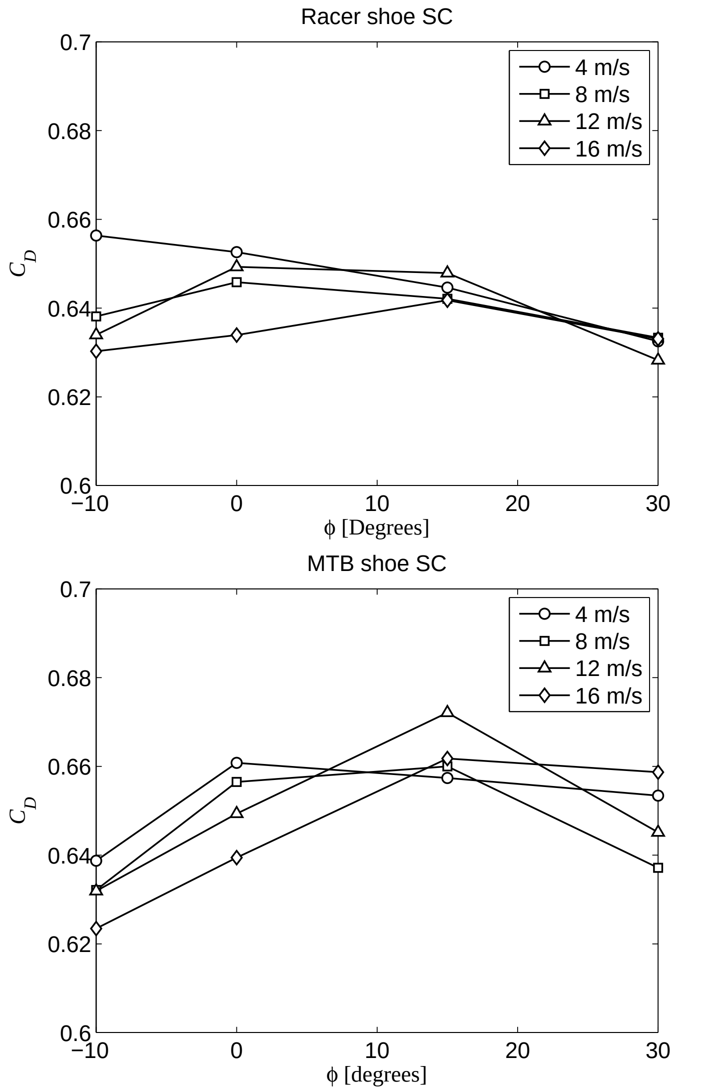

FIGURE 6.7. Figure showing C_D for Racer and MTB shoe SC as a function of angle for different speeds.

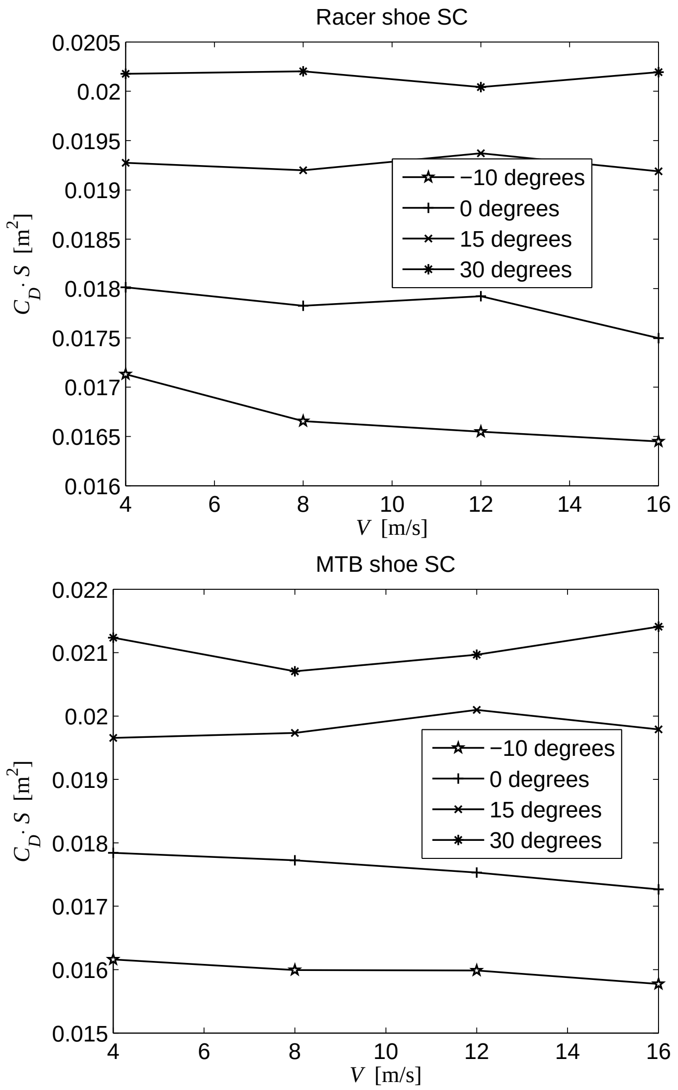

FIGURE 6.8. Figure showing $C_D \cdot S$ for Racer and MTB shoe SC as a function of velocity for different angles.

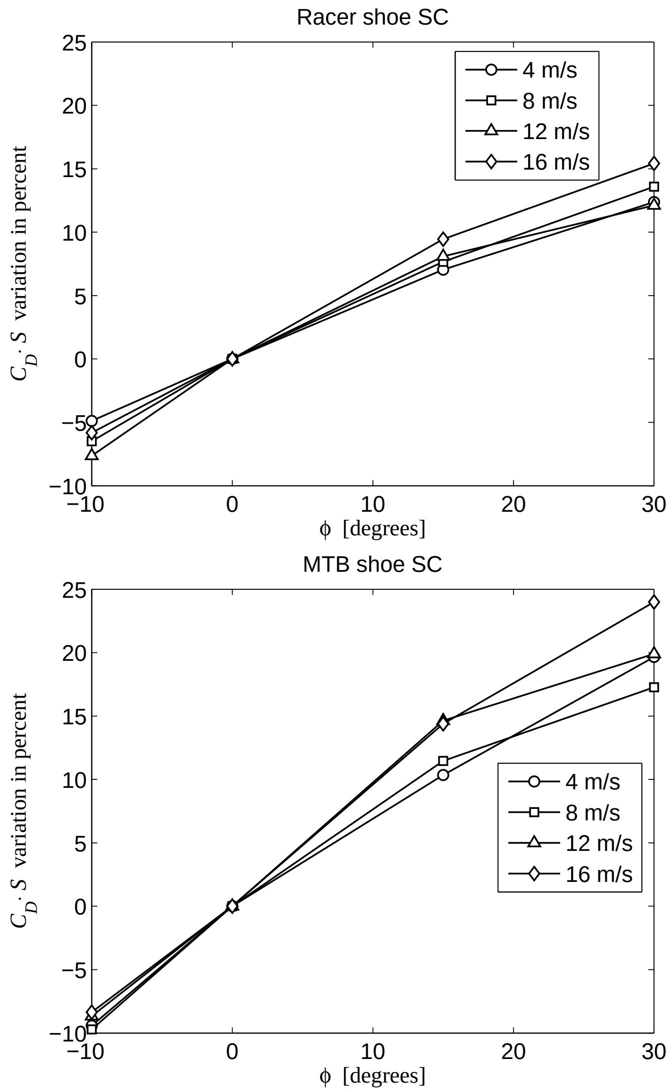

FIGURE 6.9. Figure showing reduced drag by changing inclination, normalized with 0 degrees.

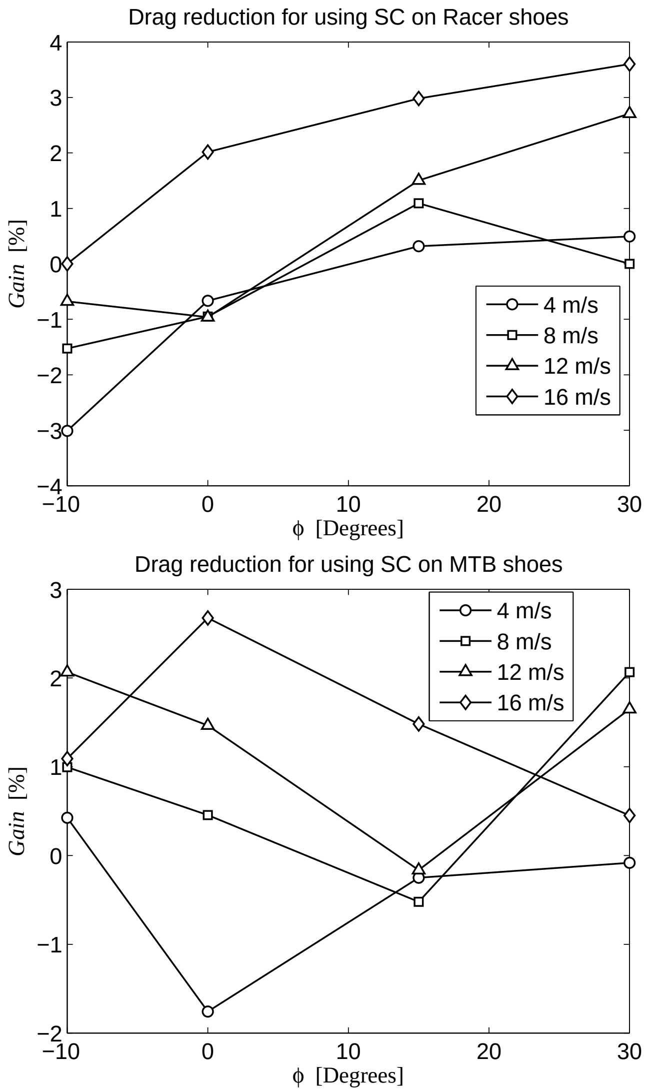

FIGURE 6.10. Figure showing reduced drag by changing inclination, normalized with 0 degrees.

CHAPTER 7

Conclusion

7.1. Shoe Cover Validation

In Chapter 3 it was stated that most elite cyclist use shoe covers to improve the aerodynamical properties of the shoe and hence create less drag. Shoe covers were tested on both the MTB shoe and the Racer shoe. Normally MTB cyclists do not use shoe covers due to the fact that they travel with much lower speed and quite frequently in upright position, diminishing the importance of the shoe contribution to the overall drag. But since the shoes are very different one might be able to draw some conclusions of the use of shoe cover.

In Chapter 6 one can see that the racing shoe with shoe cover has much lower drag coefficient for all velocities and angles than the racing shoe without shoe covers. At 15 and 30° one can see a difference of about five percent at 16 m/s. It is interesting to see how much difference the shoe cover made for the Racer shoe, at 15° it has the worst C_D and with it the best.

When the shoe cover was used on the MTB shoe one could also see some differences even if they were not as big as with the racer shoe. One possible reason for this is that the buckles on the racer shoe are much larger and not as smooth as on the MTB shoe. So by cover these it will have bigger effect on the Racer shoe than on the MTB shoe.

One should keep in mind that the frontal area with shoe cover are larger than without shoe cover. Instead comparing drag factor and hence not normalizing with the frontal area one can see how the shoes would work on track. Here the difference are smaller but at 15 and 30° it is obvious that the shoe cover is beneficial despite its larger frontal area. From this one can draw some conclusions. If one would make a new pair of cycling shoes one should avoid big buckles or at least cover them without enlarging the frontal area. Shoe covers are better than without and should be used even on shoes with small buckles like the tested MTB shoes.

7.2. MTB or Racing System

Like described in Chapter 3 the Racing shoe has a slimmer design than the MTB shoe but on the other hand it has bigger buckles that can disturb the flow around the shoe. Such disturbed(turbulent) flow can in some cases contribute to a lower drag than if the flow would be smooth (laminar). In Chapter 6 one can see the drag coefficients for the different shoes at different angles and speeds. Without shoe cover there are hardly no difference between the MTB shoe and the racing shoe. With shoe cover the Racer shoe is better at almost all velocities and angles and in some cases the margin is very big.

It is unfortunately very hard to draw any conclusions about which pedal system that is beneficial, or if it does even matter. The pedal represents a very small part of the measured object and the difference between the two tested systems are not huge. Today it exists pedals that are much smaller and hence much smaller frontal area, this would of course contribute to a lower drag and would have been interesting to test.

7.3. Time Savings?

Since the main goal with this study is to see if it is possible to ride faster with better shoes it is necessary to make an analytical model that can give us that information. The model is based on (**?**) but with some simplifications. Imagine that a bicyclist starts his 40 km long race with an average speed of 16 m/s, hence there is no acceleration that will require any force (newtons first, Equation 7.1).

$$F = m \cdot a \tag{7.1}$$

The tire friction (3 N according to **?**) in that kind of speed is neglected since it is a very small part of the total resistance and also due to the fact that it is independent of which shoes the cyclist is wearing. We also assume that one cyclist produce the same amount of power independent of which shoes he is wearing. Our swedish olympic silver medalist Gustav Larsson typically produce about 500W (A normal trained exerciser would produce about 250 W) in average during this kind of flat race. Using Equation 7.2 one can calculate the force that the rider needs to overcome to maintain this speed, this is calculated to 31.2 N which complies very well to the analytical calculations in (**?**) with the modifications mentioned in the text for low drag coefficient and small reference area.

$$P = F \cdot V \tag{7.2}$$

Since the forces in the wind tunnel has been measured one can calculate the difference between the Racer shoe SC and MTB shoe at 16 m/s. Since there are four angles, an average force difference is used, this difference was calculated to 0.144 N. Subtracting this from the old force gives us a new lower force that the rider needs to overcome. By using Equation 7.2 one can calculate a new

Shoe	Racer shoe	MTB shoe	MTB shoe SC
Racer shoe SC	15	23	6

Table 1. Time savings in seconds for using the Racer shoe with shoe covers. The force difference at the negative angle $-10°$ is not included when calculating the time savings in this table.

Shoe	Racer shoe	MTB shoe	MTB shoe SC
Racer shoe SC	11	14	-2

Table 2. Time savings in seconds for using the Racer shoe with shoe covers. In this table the time savings have been calculated using the force differences for all angles.

velocity and by combining this with Equation 7.3 a new time on the 40 km long track can be calculated.

$$s = V \cdot t \tag{7.3}$$

Comparing this with the old time one can see that he will be 23 seconds faster. In Table 1 one can see how much time the Racer shoe SC can gain versus other shoes. In Table 2 the time gained has been calculated by the mean force differences for all angles, compared to Table 1 where the negative angle is not included.

No matter how you calculate the results shows that there in this static test will be time differences between the different shoes. One should have in mind that the result might be different when dynamic effects comes into account like pedaling, side wind, spinning wheels etc.

7.4. Club feet as a validation?

In the preparation of the test the club feet were meant to work as a validation for the experimental setup. Since the shapes used are standard shapes and most of them have a C_D given in a textbook, for example (**?**). However, there were somethings that wasn't thought about. As soon as you change the angle of the club feet relatively to the ground one will get a completely different C_D due to the changed form in the wind direction. A good example of that is when club foot A is lent forward and forming a wedge thats nicely cuts the air. Compared to when example club foot C is lent forward and forms a completely flat surface in the wind direction. However, if the club feet were held leveled it might serve as a good validation and some differences between the different objects should be measurable?

In the results showed in Chapter 6 one can at zero degrees clearly see a difference between club foot A and the rest, but between the three others it is hard to really distinguish any difference. Before the test I thought that Club foot C might have a lower drag coefficient due to its smoother rear end. This can not really be seen in the graphs, instead it is club foot D that has the lowest drag for most of the speeds. D has the sharpest front compared to the others and that might have been the reason for success in these tests. One should also be aware of that it in this area of Reynolds number $(2 \cdot 10^5)$ are a lot of changes due to Re number effects (**?**) that might confuse the results.

CHAPTER 8

Discussion

8.1. Accuracy of The Measurements

When making tests like these there are several errors that can occur that will affect the result, human errors and measurement errors. If these errors are large enough they will destroy the test results and it will be impossible to draw any conclusions except the one that the errors were to large. The first thing i did during my measurements was to test how large this error was. The procedure was as follows.

1. Mount shoe model in setup rig.
2. Calibrate load cell.
3. Run the wind tunnel and measure the force at different velocites.
4. Unmount shoe model.
5. Repeat from 1.

By doing this and comparing the results it is possible to see how they differ between the runs. As expected there are differences between the measurements, what contributes most to the errors are hard to say. The test was the first series of test I did with the wind tunnel so it may depend on me. It always takes some times before you get to know your instruments and machines. Now afterwards I can draw the conclusion that it would probably have been good to do a similiar test in the end of my time in Gävle to see if there were any difference.

A standard deviation of 0.0035 was calculated, which is ± 0.54 percent of the mean value 0.6522 at 16 m/s. The deviations are pretty small and will nott affect the result dramaticly. For 4 m/s a standard deviation of 0.011 was calculated, ± 1.68 percent of the mean value 0.6507. This result is not good. One possible explanation is that the engine was cold at the test time and then has some problem with speed variations at low velocities.

CHAPTER 9

Acknowledgments

I would like to thank my supervisor Dr. Jens Fransson who has been giving me inspiration and always acted as a role model both professionally and socially. Although his great knowledge in the field he as always showed me an humble attitude.
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