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Date 13 April 1992

IMPROVING THE AERODYNAMIC EFFICIENCY OF THE RECREATIONAL CYCLISTS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Michael J. Meyers
May 1992

DEDICATION

This thesis is dedicated my parents
Mr. Richard and Ann Meyers
and my fiance Kimberly Theodore
who have supported me through all my endeavors.

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. Ralph Kimberlin, for his assistance and encouragement. I would also like to thank the other committee members, Dr. Donald Tippet and Mr. Bob Richards for their comments and assistance over the past semester. I would also like to thank the 52 other cyclists who rode the 3566 miles from Los Angeles to Boston with me across the country from May 11 through June 27 1991. Through them and the 47 day experience we shared, I have realized that anything is possible if you just put your mind to it.

ABSTRACT

This treatise has researched the modification of body position, wheels, and use of aerodynamic enhancing devices to significantly reduce the drag and increase the speed of the recreational cyclist. This thesis has evaluated several ways in which aerodynamic improvement can be made, the cost versus drag savings factor, and ergonomics. When traveling on level ground, cyclists dedicate 90% or more of their energy overcoming wind resistance or drag. Previous wind tunnel testing and outdoor evaluations have determined that the retarding force due to wind resistance increases proportionally to the square of the velocity. The two principal causes of wind resistance are pressure drag and drag produced on surface imperfections.

Pressure drag can be significantly reduced by streamlining or lowering the cyclist's frontal area and of the two causes involved has the greater effect. Drag due to surface imperfections is caused by holes, gaps, roughness, and protrusions. Reduction usually requires costly modification and therefore was not addressed here.

Outdoor testing was conducted and compared to a baseline cyclist in a racing position. Modifications were then added or subtracted one per run and the data for each run were recorded. Each configuration was evaluated during a coastdown study and at several different gearing ratios on a level course which resulted in data being obtained for a range of speeds. Wind conditions were less than two knots during all testing. Results were verified for repeatability.

It was concluded that the recreational cyclists can significantly increase speed for the same power output through the use of several different aerodynamic devices. Although cost of the devices varied, significant reductions were attained through the use a less costly alternatives.

The testing conducted for this thesis allowed the author to take important steps of obtaining knowledge through the experience and aerodynamic refinement of a fairly simple vehicle, the bicycle. Techniques similar to the ones used in this evaluation could be applied to any form of human propelled machine be it a commuter vehicle, wheel chair, an airplane, a helicopter, or a submarine.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

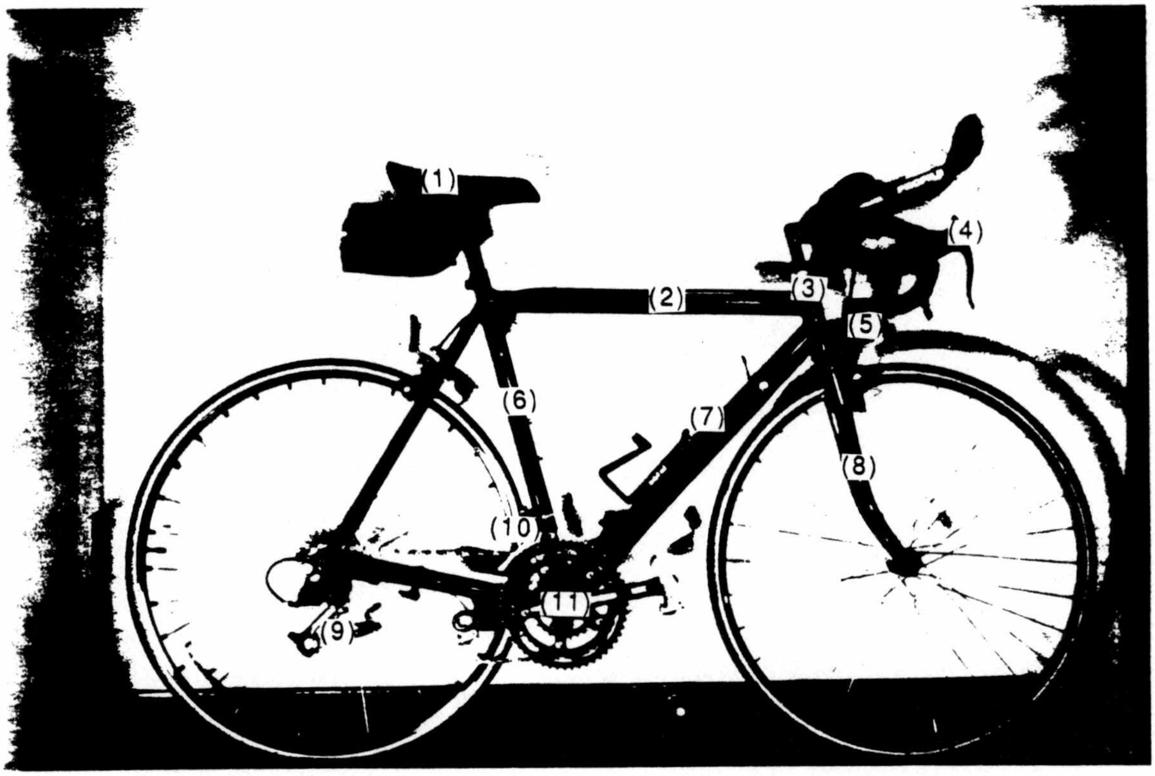
LIST OF ABBREVIATIONS

Average Speed....AVS
Bicycle Across America....BAA
Gearing Ratio....GR
Human Powered Vehicle....HPV
International Cycling Union....ICU
Scott Super Dropins....SSD
Tour De France....TDF
Ultra Marathon Cycling Association....UMCA

LIST OF UNITS

Centimeters....cm
Degree (s)....deg
Dollars....$
Feet....ft
Gram(s)....gm
Revolutions Per Minute....rpm
Horsepower....hp
inches....in
Kilometers....km
Miles....mi
Millimeters....mm
Ounces....oz
Pound(s)....lb
Pound(s) Force....lbf
Second(s)....sec

BICYCLE TERMINOLOGY



(1)	Saddle or Bicycle Seat	(7)	Cross Tube
(2)	Top Tube	(8)	Front Fork
(3)	Head Tube	(9)	Rear Derailer
(4)	Brake Hoods	(10)	Front Derailer
(5)	Drops	(11)	Bottom Bracket
(6)	Down Tube		

DROPS - Another term for the bottom hand positions on a pair of racing handlebars.

FUNNY BIKE - A bicycle with a bent or curved top tube, a rear disk wheel and a smaller front wheel. Used by velodrome cyclists and time trial racers.

GEAR RATIO - Is the ratio between the front chain ring and the rear gear selected, and is based on the number of teeth on each gear. Example: front 52/rear 13 = 4.

PACELINE - Two or more cyclist who follow a lead rider who is breaking the wind for everyone else in the group.

PACK - A group of cyclist who ride within inches of each other.

SLICK - A tire with no tread, also another term for bicycle tires that does not require innertubes.

SKIN SUIT - A one piece garment constructed from light weight fabric such as Lycra that clings to the rider like a second skin, almost as if it were painted on.

SPINOUT - The maximum velocity possible using the largest gearing ratio available on the bike.

STICK A TURN - Hugging the edge of the course or leaning into a turn at the maximum speed without having the tires slipping or skidding.

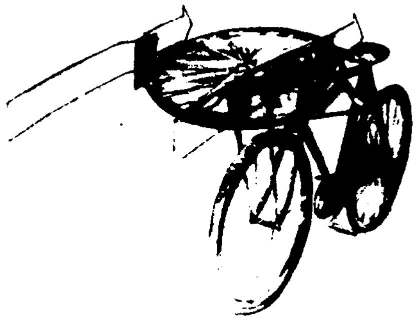
SWEET SPOT - The position when drafting that results in the maximum drag reduction when following a cyclist in a paceline.

Chapter 1

A Brief History of Bicycle Aerodynamics

One might ask how bicycles and aerodynamics are related? The answer begins with the inventors of the first successful airplane, the Wright brothers. The Wright brothers owned a bicycle shop in Dayton, Ohio, around the turn of the century. Both brothers were very mechanically inclined and inquisitive in nature. During the winter season, when bicycle sales were slow they would spend their time studying the principles of gliders powered flight. They constructed small models of wings and would test them on a wheel rim mounted on the handle bars of a bicycle. A picture of this setup is presented is presented below in figure 1. One side would have an airfoil shape, while the other had a flat plate. The Wrights were then able to estimate the lift of the test airfoil by turning the wheel to match the drag effect on the flat plate.

Figure 1
Bicycle Test Setup



(Kyle, Air & Space February/March 1990, pg 91.)

This cheap and easy innovation helped them refine their designs prior to their construction of a wind tunnel. They would simulate the wind or forward speed by testing the airfoil shapes in essence creating their own wind tunnel. Many historians attribute the success of the Wright brothers to their mechanical talents developed in their bicycle business. They were more practical minded than theorist, although they did spend a good deal of time corresponding with Otto Lilienthal on the theory of flight.

Downhill skiers, ski jumpers and speed skaters have been working with aerodynamics for years a crouched skier reduces drag by 50% (Whitt, 1990). They have put athletes in wind tunnels and on top of moving automobiles for evaluations in order to optimize their aerodynamic shape. Tight Lycra clothing is used to reduce parasite drag. Equipment was reshaped so that drag counts could be reduced. Although the 1930's to the late 1970's bicycles changed very little in aerodynamic performance, (Kyle, June 1987).

In the 1988 summer Olympics, Olympic sprinter Florence Griffyn Joyner used a Lycra cover over her hair hoping tis would give her a slight tenths of a second edge. Meanwhile starting in the early 1980's, velodrome cyclists were reducing the bicycle's weight and optimizing their aerodynamic profile to make them competitive. Road racing cyclist were constantly shaving down the weight on their bicycles by drilling holes in components and experimenting with frames made of various materials such as chrome molybdenum, aluminum, titanium, and composites. All this was done in the quest for those extra seconds or sometimes milliseconds that would make the difference in the outcome of the race. Although there was some research being done on bicycle aerodynamics most of the innovations were occurring in materials and components. Aerodynamics were not taken seriously until the 1989 Tour De France.

The Tour is the premier event of cycling. The race covers thousands of miles and lasts for weeks encompassing every type of terrain and challenge possible. In 1989, the close battle for the lead or the yellow jersey between a Frenchman Larent Finion and an

American Greg LeMond. Both athletes were equal in experience, size, weight and in superb physical condition. After the weeks of racing the final stage of the tour was a 27 kilometer (16.78 mile) time trial in Paris. Finion was ahead by 50 seconds, and although LeMond was considered the better time trialist, it was not considered that he could make up the time deficit to win the tour. But Greg LeMond had one advantage; he had worked very hard on bicycle aerodynamics. Prior to the season and during the race he modified and refined his position on the bike and his equipment in order to minimize his cross sectional area, in effect making him faster for the same amount of power output. A time trial is called the race of truth, because the cyclist is required go all out, holding nothing in reserve. The racer cannot draft off of anyone so that any speed gained during his maximum output is critical to his or her competitiveness.

LeMond started the race knowing he had to make this race against time his best ever. Through time spent in wind tunnels he knew how to optimize his body shape. The equipment he used was a lightweight bike, a pair of clip-on aerobars, a rear disk wheel, a tight fitting Lycra body suit, and an aerodynamically shaped helmet. As the time trial went on he was reducing his overall time on the leader Finon, with every checkpoint. He ended up beating Finion by nine seconds, the closets victory in the Tour's history. Two equal athletes and thousands of miles of hard racing, and the victory had come down to the difference in the aerodynamic efficiency of the two cyclist. LeMond's aerodynamic advantage netted him the Tour's first prize of around $360,000 plus millions of dollars in advertising contracts, and altered the cycling industry of the future.

Upon the success of LeMond's time trial, the bicycle consumer market became deluged with all types of equipment. Each new component manufacturer cited the aerodynamic efficiency of their products, but at what cost. Exotic wheels and bicycle parts were manufactured from airplane grade materials and composites. Some were very expensive, costing from thirty dollars to thousands of dollars for a completely outfitted bicycle. The recreational cyclist is always interested in ways of increasing his speed for the same amount of energy output. The question is what to buy and at what time savings. As was found out by many a cyclist, an increase in cost of the components doesn't necessarily result in a significant decrease in time trial time or even a reduction in the trip around the neighborhood. Bicycle magazines and books such as those listed in the bibliography have attempted to educate the consumer with some success. The constant innovating and updating of designs make what was yesterday's hot aerodynamic equipment today's dog.

Chapter 2

Introduction and Purpose

Introduction

This treatise has researched the modification of body position, wheels, and use of aerodynamic enhancing devices to significantly reduce the drag and increase the speed of the recreational cyclist. When traveling on level ground, cyclists dedicate 90% or more of their energy overcoming wind resistance or drag, (Kyle, June 1987). It is a known aerodynamic principal that the retarding force due to wind resistance increases proportional to the square of the velocity. The two principal causes of wind resistance are pressure drag and drag as a result of surface imperfections.

Pressure drag is defined as the drag resulting from the pressure variation over and behind a surface or body. This type of drag can be significantly reduced by streamlining or lowering the cyclist's frontal area and of the two causes involved has the greater effect. Drag due to surface imperfections is caused by holes, gaps, roughness, and protrusions. Reduction usually requires costly modification and therefore was not addressed here.

As an aid to the reader, a diagram of a bicycle designating certain components and a list of cycling terminology are presented at the beginning of the text.

Purpose

The purpose of this thesis was to investigate how much time savings over a flat measured course can be realized through refining the aerodynamics of a recreational cyclist. The definition of a recreational cyclist for this treatise is an individual who rides three to seven times a week for fitness, averaging 25 miles per outing with an occasional 100 rides on the weekends. The cost versus drag savings factor, and ergonomics involved were also addressed. Previous research was analyzed and actual test runs were conducted to investigate and refine the alternatives available to the recreational cyclist to optimize his or her aerodynamic profile. This study is of value to the recreational cyclist who typically spends a significant amount of money for small increases in speed. In the heart of many cyclist is the thought of being a racer, whether it is a competition with club members, in an organized event, or against the clock.

Chapter 3

Literature Review

Cyclist and Resistance

What makes a cyclist goes fast in order of importance is; the athlete, aerodynamic efficiency, tires, and total weight of the cyclist and his equipment. At speeds less than 10 mph, rolling resistance is equal to air resistance on the cyclist. At increasing speeds, rolling resistance essentially remains constant while air resistance steady increases with the square of the cyclist's velocity. On a level road at speeds from 20 to 50 mph, 90% of a cyclist's energy is spent trying to overcome the forces of wind resistance. Without aerodynamic modifications or shielding, the maximum speed a cyclist can hope to attain is around 40 mph (Roosa,1989).

Aerodynamic components are most effective at speeds greater than 20 mph. At this speed, approximately two thirds of the total wind drag is due to the body of the cyclist and one third is due to the bicycle on which he is riding, (Kyle, Aug 1990). Over the years there have been several design modifications that have reduced the air drag apposing the cyclist. One of these attempts in the recumbent bicycle. A recumbent bicycle rides much lower to the ground than a standard bicycle; in fact the rider sits in a chair and steers using an assembly located below his seat. Although there are many advantages to the recumbent bicycle, low visibility of the rider and the loss of power during climbing when compared to a standard bicycle tend to keep the design in the shadows. Recumbent bicycles are illegal in most sanctioned bicycle races.

Bicycles are more efficient than the automobiles that we drive. Cars at 55 to 60 mph have 50% spend of its power to over come the retarding forces caused by tires and bearing friction. In comparison, a cyclist looses looses10 percent of his power to friction and tire looses at 20 to 30 mph (Kyle, May 1988). Cycling takes one third less energy when based on a equivalent distance than walking or running (Kyle). Dirty bicycles though are like dirty aircraft. A dirty bike will result in a noticecible drag increase at speeds up to 35 mph (Kyle, 1979). When attempting to reducing drag of a cyclist just as with an airplane, items should be aligned behind each other to minimize drag and optimize performance.

Bicycle System Efficiency

The efficiency of the bicycle system is only as good as the addition of its component efficiencies. The following is presented to give the reader an appreciation for typical values of the separate components. The efficiency of a well lubricated and clean chain can be as high as 98.5% (BS140). There is only a 1% loss of power from transmission of the power from the legs to the pedals. Clipless pedals that resemble a downhill ski binding were developed around five years ago. Using a clipless pedal, a cyclist can double the effectiveness of his pedal motion because power can also be applied on the upstroke. Total bearing friction losses are around 1% for the bicycle while the cyclist looses about 2% of his power overcoming joint friction in his body. An overall mechanical efficiency for the cyclists and bicycle system has determined to be 95%.

Previous Wind Tunnel Testing

Wind tunnel studies of bicycling have been conducted over the years at several test facilities, the most noteworthy being, California State University at Long Beach, University of California at Irvine, and Texas A&M, (Kyle, 1987). The cost of wind tunnel time at these facilities ranges from $500 to $1000 an hour. In wind tunnel studies, reduction in the cyclist's drag is so subtle that it is usually measured in grams as compared to the drag of automobiles or aircraft which is measured in pounds. Wind tunnel testing usually is done with a motionless bicycle and therefore is an incorrect representation of the ground plane and the rotating of components. Outdoor coastdown tests on low wind days have been proven to compare favorably with wind tunnel test data (Kyle, 1979). There is considerable evidence based on past testing to approximate the coefficient of drag for a cyclist in the racing configuration or down in the drops, to be approximately 0.9 based on frontal area (Whitt, 1990).

Shaving the legs of the cyclist will only save about seven seconds during a 25 mile time trial (Kyle, 1987). Professional cyclist shave their legs to minimize skin abrasions during accidents and to make it easier o massage their legs after a long ride or race not for any aerodynamic benefit. Silcon sealant placed in the exterior gap between the rim and the tire saves the same amount of time as shaving legs or about seven seconds per 25 miles (Kyle, June 1989). Exposed brake cables add 18 grams per foot (Kyle), this drag can be eliminated by re-routing cables inside the bicycle frame and by wrapping the brake cables to the handlebars using standard handlebar tape.

A fairing attached to the back of the bicycle seat has shown to reduce drag by half a pound at a speed of 25 mph (Zahradnick, June 1991). The cyclist can reduce drag by a half a pound at 25 mph if the standard 36 spoke wheel is replaced by a solid disk wheel (Zahradnick). In a wind tunnel at 30 mph a standard 27 inch diameter, 36 spoke wheel weighing 710 gm generates 211gm of drag per wheel when fixed and 315gm of drag when rotating (Kyle, July 1988). The spokes of a wheel act like an egg beater, whipping at the air in a circular motion.

Riding "in the drops" or what the author calls the race position results in approximately 9.03 lb of drag (Drake, May 1990). Using clipon aerobars, as depicted in figure 2, for this same cyclist has shown in wind tunnel tests to reduce the drag to 7.44 lb which results in a four minute time savings over a 25 mile course. In 1991, Greg LeMond worked with Scott Manufacturing to develop what are called "dropin" handlebars. A picture of the dropin handlebars are presented in figure 3, below. The new dropins resemble standard racing handlebars except at the bottom where other handlebars stop the dropins add an additional section that is bent in 90 from the bottom of the bars and then attached in the middle ahead of the head tube. During wind tunnel testing in early 1991 LeMond was able to achieve his lowest drag profile using the new dropin handlebars. Another advantage to the the new dropin bars can be used during mass start bicycle racing because the bars do not endanger other riders.

Figure 2

Picture of Aerobars Mounted on Racing Handlebars

(From the Performance Bicycle Catalog, Spring 1992)

Figure 3
Picture of Dropin Handlebars

(From the Performance Bicycle Catalog, Spring 1992)

Cycling athletes have followed their down hill slalom and speed skating counterparts by incorporating the use of aerodynamic dynamic enhancing clothing. Most cycling clothing now incorporates Lycra as a primary component. The stretched and tight fitting fabric slips through the air better than any other. Cycling clothing has come a long way from the the wool tight and cotton jersey days. One piece custom made skin suits are now in the wardrobe of any serious racing cyclist. At 30 mph, a cyclist wearing a Lycra one piece skin suit can reduce drag to 5.84 lb or 7.5% less than the same rider wearing standard Lycra shorts and a wool long sleeve cycling jersey that results in 6.31 lb of drag (Nonweiler). The disadvantage to the one piece cycling suit is that the Lycra has a tendency to keep heat in and increase the cyclist's body temperature when riding long periods of time on hot days.

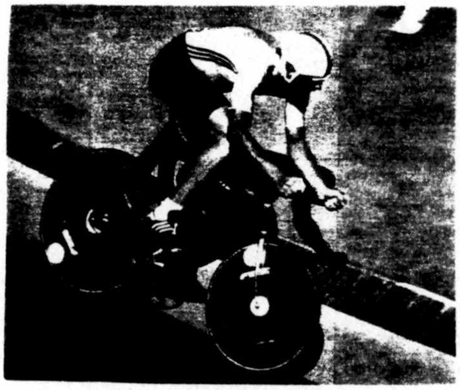
Olympic Development and Funny Bikes

From the mid 1980's to the present, design and construction of racing bicycles has changed drastically. The first developments came from the track racing arena. Track bike racers ride on a velodrome which is an oval banked track, usually outdoors, made of smooth concrete. Velodrome curves can be banked as much as 50 degrees with the the track steadily increasing in slope as the cyclist progresses up the sides of the track. This banked track requires minimal maneuvering when compared to regular road racing. The optimum weight for a world class sprinter that races at veldromes is around 200 lbs of solid muscle. Track bikes use no brakes and have a fixed rear gear eliminating the need for cables, derailer, and shifters. The absence of these components reduces the drag of the track bike when compared to a standard road bike.

Low profile or "Funny bikes" were first used in the 1984 Olympics, see figure 4 below. Funny bikes get their name from the unique frame geometry and wheel combinations. The frames top tube slopes down and is usually curved. The front wheel is considerably smaller than the back wheel. Both wheels are usually solid disks. The rear disc wheels are heavy to conserve momentum and are design to act like a flywheel. The tires are high pressure slicks with little or no tread. Typical drag numbers using a track bicycle at 30 mph, with the front wheel and back Kevlar disc wheels having diameters of 24 and 27 inches respectively is around 1.21 lb. With a rider the drag is increased to 6.56 lbs (Kyle, July 1988).

Figure 4

Picture of a Funny Bike



(Bicycling, Dec 1988, pg 36)

Optimizing Body Position

The most significant contribution to drag reduction is optimizing the cyclists body position. This is achieved through the combination of several variables; seat height, forward and aft saddle position with respect to the bottom bracket, lowering the handlebar stem, and the use of aerodynamic enhancing components. The ultimate goal in body position is a flat, horizontal back and narrow sides. The flattening of the back is optimized by raising the seat and lowering the handlebars. If the cyclist's back is humped lower the bar height or rotate the hips while riding. Rotation of the hips, though can be fatiguing during long rides. The flat back position requires months for a cyclist to get comfortable with and is best done by changing one thing at a time. This is achieved by either adjusting the seat or the handlebars in small intervals over several weeks or months until a flat back is achieved. Elbow position is optimized by bringing them to a position equal to or slightly less than shoulder width. Aerobars aid the rider in maintaining the optimized position through supporting the upper body during long rides.

Torso to thigh angle should be about 30 degrees to not inhibit breathing and so that knees don't hit the cyclist's chest while pedaling (Drake, May 1990). Body frontal area and resulting wind resistance increase with the riders height squared (Kyle, July 1988). At 20 mph a cyclist in the racing position pushes the equivalent of about 1000 lbs of air out of his path per minute (Roosa). But there is more to drag than just frontal area. The shape and smoothness of the cyclist's body also plays an important part. Past studies indicate the most aerodynamic improvement comes from modifying and optimizing a cyclist's body position (Roosa).

Aerodynamic components effectiveness is dependant on the body to bicycle interface, the size of the rider, and effective use of body proportions or fit. Bicycle to body interface is how smoothly and naturally a cyclist meshes with the five points on the bicycle that are in contact with the body, namely; the two pedals, the two points at the handlebars (or four in the case of aerobars), and the bicycle seat. Proportional fit refers to the proper relation between the frame geometry and the length of the body parts of the cyclists. When the above two elements are optimized a rider can maximize his power out while also minimizing his aerodynamic drag. If the seat is adjusted too far forward then climbing power is compromised. If the seat is too far aft then the rider's weight shifts back and frontal area is increased.

In order to be positioned farther forward cyclist tilt the saddle down two to five degrees. Professional triathletes like Mike Pigg, sit extremely forward with their center of gravity aligned or slightly ahead of the bottom bracket. Some studies have shown that with the seat in this position power overlap of the quadriceps and the gluteus maximus occurs optimizing performance and range of motion when compared with the standard saddle position (Niles).

Also with Mike Pigg's forward saddle position more weight is placed on the front wheel. Forward adjustment is not much, for most people, 6 cm forward of the standard saddle position is sufficient. Greg LeMond moves his seat forward about three cm and then moves forward three cm on the saddle when using his aerobars, this allows him to shift his weight back when he is required to climb. When using aerobars, the rider should keep his chin below his hands to eliminate any possible gap that could trap air (Drake, May 1990).

For the racing position, wind tunnel testing has determined that 32 lb drag force aposes the cyclist and his bike at a speed of

72 mph, (Zahradnick, 1989). Crosswinds from 20 degrees to the right or left of the cyclist increase drag of the bicycle and the rider by 10%.

Aerodynamics and Bicycle Frames

The International Cycling Union (ICU) is the governing body for global racing competitions. All equipment used by competing cyclists must be within the restrictions and regulations of the ICU. In 1991, frame regulations were amended to allow tube diameters in excess of 45mm round and 75 mm oval/aerodynamic shape. This change in the long standing restriction now allows for more experimentation in frame design. Some frame builders have branched off from the traditional diamond configuration for design that favor aerodynamic efficiency.

Bicycle frame design is a compromise between lightness and rigidity. Light frames have less inertia but typically flex more. A flexing frame robs cycling power from propelling the bicycle forward. Frames are now constructed of several metal alloys and composite fabric. Aluminum bicycles were favored by many cyclists over the last seven years. Using aluminum instead of steel alloy has two major disadvantages. One, welding aluminum weakens the tubing, and two, aluminum is not characteristically good at enduring cycling stresses.

Frame tubing cross section is now favoring something other than the traditional round shape. Round tubing takes on the principles of cylinder in turbulent flow. Several types of experimental shapes have been evaluated and compared to a standard round tubing. During wind tunnel tests conducted in 1988, Chester Kyle determined the following results:

Windtunnel Tubing Study

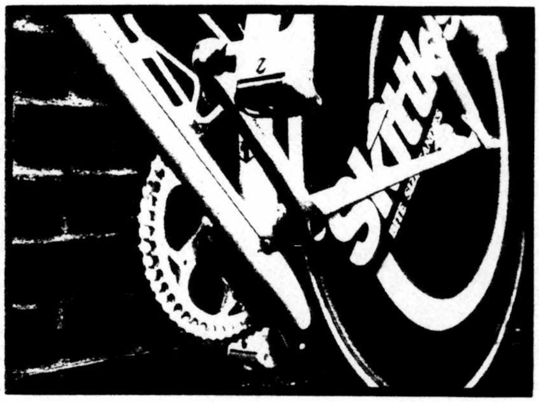
Tubing Dimensions (in)	Length to width ratio	Drafting (1)	Not Drafting (1)
Round 1.162	1/1	76.1	32.3
Helicopter Symmetric Strut 2.83X0.93	3.05/1	28.5	- -
Helicopter Symmetric Strut 2.36X0.98	2.41/1	42.8	8.1

Note (1): Denotes Drag in grams/ft of tubing. Drafting is considered when a tube is located behind a front wheel.

Designers ar now exploring several ways to reduce drag associated with frames. Bicycles with "tails" (a tapered fairing behind the seat of the cyclists) are now allowed under the revised ICU rules. Aft fairings were banned from 1986 to 1991 after Thierry Marie used this type of fairing to win the prologue time trial in the the 1986 Tour De France. The new Yamaguchis frames to be used in the 1992 Olympic games incorporate a four inch extension below the bottom bracket in an attempt to smooth the flow and aerodynamically fair the back wheel and tire. The extension is presented in figure 5 below. Several years ago, Trimble began building Monocoqued bicycle frames that have a symmetrical airfoil shape. Although banned from racing until recently, the frame has had some success with higher end racers. The Trimble frame though, suffers crosswind effects similar to a diskwheel.

Figure 5
Four Inch Extension Below Bottom Bracket

Yamaguchis also sport an aero-shape down tube that extends 4 inches below the bottom bracket shell to fair the rear tire.



(Bicycling, Aug 1991, pg 96)

Handlebar Modifications

Present day handlebars that allow riders to maintain several different positions. Handlebars were revolutionized with the invention of the aerobar. First introduced in the the 1980's, aerobars were the brainchild of an alpine ski coach named Boon Lennon. This new type of handlebars or clipon adapters allows a cyclist to simulate the tucked profile of a downhill skier. In the 1989 Tour De France, Greg LeMond used a pair of clipon aerobars to make up a 50 second time deficit during the last stage, a 16.78 mile time trial. The defeated rider, Finon, who that day used what is called cow horn handlebars, later used a pair of clipons to set a race record in France (Gould).

Previously discussed testing indicates that the use of aerobars can reduce drag by 10%. In order to optimize the advantage of aerobars requires a cyclist must shift his weight forward by about six cm. Failing to shift weight forward may counteract any benefit gained from aerobars. Riding in the drops or racing position as compared to the touring position shaves 40 sec of a 25 mile time trial (Drake, May 1990). Wind tunnel tests indicate that the optimum angle for aerobars is somewhere between horizontal and 30 degrees up. Using aerobars, a cyclist can expect to increase his speed by one to two mph for a given power output (Drake).

Another type of handlebars developed during windtunnel testing in early 1991 are call Scott Super Dropins (SSD). SSD's resemble standard racing handlebars with an additional lower cross level located at the bottom of the bar. SSD's are legal for mass start road racing and allow the rider a narrower grip, and to bring the elbows in closer to the body. Because the rider's hand positions are low and close to the head tube, some cyclists have experienced shimmy resulting from reduced lateral stability at high RPMs (Zahradnick, Aug 1991). A rider using SSD's can typically reduce drag by eight to nine percent.

LeMond also has been testing a cable arrangement of two separate pairs of bicycle cables that run from the middle of the front fork to the bottom of the SSD's. The additional cables help to reduce upward bending and flexing that occurs when a rider is sprinting and climbing up hills.

Using regular handlebars a cyclist can reduce drag by 31% when in a full tuck position as compared to the same rider in the touring position (Kyle, Aug 1990). A full down tuck is a position where the elbows are in, the knees are squeezed on the top tube hands are located on the top of the handlebars and the chin is placed on top of the hands. The tuck is usually used on descent because it is difficult for the rider to peddle in the compact position. From my personal experience, the tuck position is very uncomfortable and can be dangerous to use at high speed because hands are away from the brakes. Aerobars provide almost the same drag reduction as the tuck position but aerobars allow the rider to maintain better control and visibility on the bicycle while also allowing the cyclist to pedal comfortably.

Aerobars help to conserve rider energy on long rides because upper body is supported by skeletal structure between the elbow and the shoulder. On bumpy roads aerobars can fatigue the cyclist because the road jarring is transmitted directly to the torso as compared to a rider in a racing position when the arms act as shock absorbers. Most clipon bars come in a variety of widths. It was thought that the closer the elbows are brought together the more the frontal area of the cyclist can be reduced thus reducing drag. Although this is true, practice has shown aerobars that bring the cyclist's elbows in closer than six inches are very uncomfortable and therefore any possible advantages are lost by the decrease of handling qualities and comfort. It is now generally accepted that maintaining small widths is not important, as long as the rider does not exceed shoulder width. This is the most efficient compromise between comfort and aerodynamics.

Wheels

Once again the ICU plays an important part in what can be used by competing cyclists and this in turn effects what's available to the consumer. Most dedicated cyclists desire models that are sporty and could be raced if they later had the desire to enter the sport competitively. According to ICU regulations, wheels can have a maximum diameter of 700mm and a minimum diameter of 550 mm. The maximum allowed width measured from the inside face of each dropout, or the place where the frame mates with the wheel hub is 105 mm and 135 mm for the front and back wheels, respectively (Zahradnick, June 1991).

Funny bikes usually incorporate a smaller front wheel to reduce weight and drag. Bicycles produced by the Lotus Bicycle Company are termed proportional bikes, that incorporates a smaller wheel in the front but this is more for the comfort of smaller riders, usually women, and is not purposely driven by aerodynamic considerations. Smaller wheels have less drag but more rolling resistance which in most cases counters any benefits of reduced drag. A simple method for a cyclist to reduce drag counts by 60gm is by replacing a 25 or 20 mm tire with a 18 mm tire, this results a 25 second saving during a 25 mile time trial (Kyle, 1987).

A different method to gage cyclist's power output is to measure the amount of VO_2 (oxygen uptake during exercise) consumed under varying conditions. Some work has been done to eliminate the number of spokes from the standard 36 down to as low as 16 per wheel. Testing conducted using an 18 spoke rear wheel and a 16 spoke front wheel resulted in a VO_2 savings of 7% over standard spoked wheels. The smaller number of spokes, though does make the wheel durable enough to use under road conditions (Hagberg).

This is the way the experts (Roosa) improve aerodynamics of standard wheels. Most contemporary rims are 19 to 16 mm wide, and an 19 or 18 mm tire should be used to match the width of the rim. The rim and tire combination form the approximate shape of an ellipse which is fairly neutral aerodynamically. Optimally, tires should be 2mm wider than the rims. Reducing the number of spokes from 36 to 24 will reduce drag while also allowing the wheel to sufficiently carry the load of the bicycle and the cyclist under most riding conditions. Additionally, standard round spokes should be replaced with elliptical ones.

Disc wheels have been used for more than 40 years. The first disc wheels were constructed out of plywood and were used for veldrome racing. The use of composites have allowed disc wheel design to become very complex in design and expensive. There are two types of disk wheels; flat disc and lenticular shaped. Using disc wheels in crosswinds can be very tricky particularly on the front wheel that steers the bicycle. In crosswinds the center of pressure of the disc wheel is located forward of the wheel hub resulting in the front wheel having the tendency to "weather vane". Reversing the front fork during cross winds moves the maneuvering axis aft, closer to center of pressure allowing the front wheel to become more stable (Kyle, Mar 1990). However the trade here is that at slow speeds the reversed fork has the tendency to make the bicycle unstable.

To counteract the side effects on disk wheels during crosswinds several manufacturers have developed three, four and five spoke composite wheels. The spoked composite wheel are structurally more complicated and the earlier versions were prone to structural failure. The cross sections of these three to five spoked wheels are either elliptical or a symmetric airfoil shape. Testing has shown these composite wheels to have equal or slightly better performance then a disc wheel (Kyle, Aug 1990).

Water Bottles

Water bottles are necessary for cyclists who ride for extended periods of time over 45 minutes. Without water a cyclist will have a tendency to overheat on hot days. Some research and testing has been done to refine the aerodynamics of water bottles. Aerodynamic or bottles that tape on the shaped of a symmetrical airfoil section can reduce drag by 40 gm or shave 15 seconds off of a 25 mile time trial (Kyle, Jun 1987). Water bottles can add up to two extra lb of drag, if the bottle racks are removed or mounted behind the cyclist's seat 90 seconds can be saved during a 25 mile time trial (Drake, May 1990).

When a cyclist reaches down for a water bottle or turns his head he significantly increases frontal area (Roosa). Tests have shown that reaching for a water bottle located on a cross tube increases drag by 1.25 lb. If a cyclists reaches for a water bottle ten times during a 25 mile time trial he adds 45 sec to his time (Drake, May 1990). Some researchers have determined that placing the water bottles behind the seat can reduce drag overall. The more favorable location may be also be a result of the rider having reach for a water bottle from behind which is more aerodynamic than reaching down.

Triathletes are now using a product that became available on the market in 1990 called a Camelback Water Carrier. Instead of reaching for a water the rider wears the water backpack and sucks water through a tube. The Camelback is sleek and aerodynamic looking although no data is ready available on its drag performance. Another alternative is a rubber water bladder that is mounted below the rider's seat. It fills up with water much a balloon. A tube is then attached to the top tube of the bicycle frame and runs up the handle bars. By sucking on the tube that is located right in front of the cyclist, the rider retrieves water while still maintaining an aerodynamically enhancing profile.

Clothing

Studies conducted by Nonweiler in 1956 indicate loose clothing can increase drag by up to 30% of body drag which results in a 42 second increase during a 25 mile time trial as compared to the same cyclist wearing tight fitting clothing. Most cycling clothing today incorporates Lycra that helps the clothing cling to rider thus minimizing the drag as a result of wrinkles or bagging fitting clothing. More on cycling clothing is presented in chapter 4 under the description of the equipment tested.

Accessories

Until the early 1980's, accessories were designed to make them as light and reliable as possible. This has now changed, and brake and shifting cables are now re-routed and even water bottle cages are redesigned smoothing out material and minimizing rough edges or bumps. Shifting levers are now being incorporated into braking levers. Not only does this eliminate the need for mounting the shifting levers on the frame, it also allows the cyclist to maintain their position on the handlebars. Brake cables are no longer left in the airstream; they are wrapped to the handlebars. Because they are in line with the bicycle frame, center pull brakes also provide some aerodynamic advantage over side pull brakes.

Over the last eight years manufacturers have worked to improve the aerodynamic shape of bicycle helmets. This is an outgrowth once again of the down slalom community. Helmets available today are light, crash resistant, and some even incorporate a teardrop shape or tail in the back. Many riders don't realize though, that the aerodynamic benefits of shaped helmets are lost when the rider looks down or from side-to-side.

Velodrome Versus Road Use

What works well in the confines of a velodrome doesn't necessarily work well for everyday road use. Many aerodynamic components can be dangerous when used in packs or groups of riders. Pack riding requires split second control and immediate access to brakes to prevent accidents or injury. In a pack, riders bounce off of each others shoulders, and wheels are separated from each other by inches. ICU ruling on aerodynamic components states that road race bike must not present any danger to the competitors (Zahradnick, June 1991).

Low profile bikes used in track racing do not corner well and are difficult to steer because the rear discs used is rigid. With a regular road bike the spokes bend sideways and help the cyclist "stick" when in a turn. Track bicycles are also not good for road use because of the dynamics of stopping and erratic pace of racing; speeding up and slowing down and rough road surfaces encountered. Track bikes are designed to conserve momentum while road bikes are designed to be quick and responsive. In comparing the design requirements for both types of racing, the optimum weight for a male endurance cyclist is a lean, 160 lbs while the weight for a world class velodrome sprinting cyclist is stocky, 200 lb.

Climbing and Crosswind Effects

As a result of the slow speeds and power requirements during climbing, light weight components especially frames are most important, aerodynamic devices just represent additional weight that has to be lugged up the hill. Professional cyclist Andy Hampsted remarked that the additional load of just a few of ounces on a new component can be noticed during climbs in excess of 45 minutes (Drake, Set 1990).

Drafting

Drafting is a technique were the cyclist follows directly behind one or more cyclists or moving object in order to reduce the amount of drag forces applied to the drafting rider. In cornering or crosswind conditions the cyclist keeps the object between himself and the wind. The drafting cyclist searches for the "sweet spot" or the position where there is the maximum energy saved. The cyclist knows he has reached the sweet spot because wind noise is significantly reduced. When cyclist draft in a group, the motion is very sophisticated. A paceline of cyclists usually requires riders to keep their tires within inches of each other. The lead rider will ride up front from one to three minutes then peal off to the side and fall back to the end of the line while the rider who was directly behind him assumes the lead. This fluidity can go on all day and it helps the riders to go much faster working together than if they were working against the wind alone.

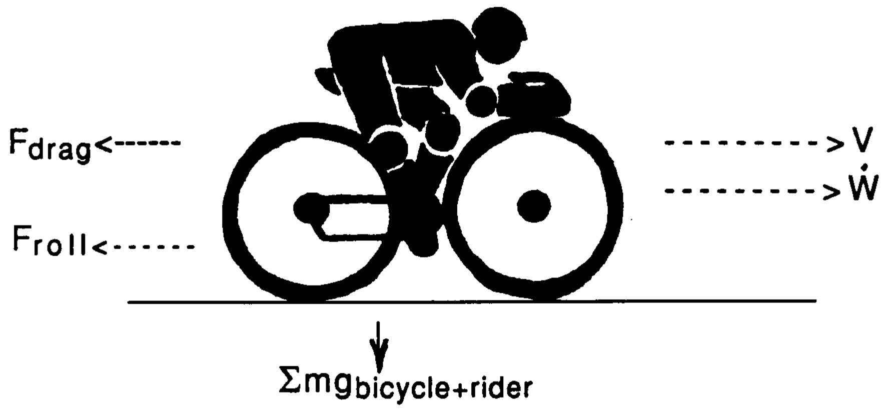
Riders in a pack were studied using oxygen uptake or VO_2 consumption as another way of measuring workload (Hagberg, 1990). He found that pack riding reduces wind resistance for the cyclists within the pack by 30%. The cyclists in the front are in effect breaking the wind for everyone behind them. Two or three cyclist in a paceline at 25 mph reduce their power required by 27% when behind the leader. If a cyclist follows a pickup truck going 25 mph he can reduce his VO_2 uptake by 62%. For a pack of 8 to 20 riders, VO_2 was reduced by 39% for the cyclists inside the pack (Hagberg, 1990).

Equations and Aerodynamic Theory Involved

There are several equations that are of interest when analyzing the aerodynamic efficiency of a cyclist's relationship between power and speed, the power required, the rotation kinetic energy, the pedaling force equation, the drag and coefficient of drag equations. A free body diagram of a cyclist is presented in figure 6:

Figure 6

Free Body Diagram of a Bicyclist



(Logo used with permission of Pedal for Power, Inc)

As shown previously, a bicycle is very efficient. The power required at the pedals of the bicycle on a level, smooth and hard road is the following (Whitt, 1990, pg 157):

$$\dot{W} = (V/\eta_{mech})\{\Sigma(mg)[C_r + s/100 + a/g(1 + m_w/\Sigma(m))] +0.5(C_d A\rho)(V + H)^2\} \quad \text{eq (5.1)}$$

where:

$\dot{W}$ = power required

η_{mech} = overall mechanical efficiency

$\Sigma(mg)$ = Summation of the weight of the rider and the bicycle

C_r = coefficient of rolling resistance

s = upslope in percent

a = is the acceleration of the bicycle

mw = effective rotational mass of the wheels and tires at the outside diameter

H = speed of the headwind

V = speed of the bicycle

C_d = coefficient of aerodynamic drag
A = frontal area of the rider plus bicycle
ρ = air density
g = gravitational constant

Assuming that the cyclist is not accelerating, and is riding on a level course with no headwind and an overall mechanical efficiency for the cyclists and bicycle system can be assumed of 95%, (5.1) can be simplified to the following:

$$\dot{W} = V/0.95\{[\Sigma(mg)(C_r)] + 0.5(C_d A\rho)V^2\} \qquad \text{eq (5.2)}$$

From Bicycle Science pg 86 we have the equation for drag force:

$$F_{drag} = C_d\rho(V^2)A/2 \qquad \text{eq (5.3)}$$

where:

V = relative velocity (when there is no wind)
g_c = gravity constant

From Bicycle Science pg 157 we know that the rolling force of the wheels in contact with the road is the following:

$$F_{roll} = \Sigma(mg)(C_r) \qquad \text{eq (5.4)}$$

Simplifying equation (5.2) by using the results of equations (5.3) and (5.4) we have the following:

$$\dot{W} = (V/0.95)(F_{roll}+F_{drag}) \qquad \text{eq (5.5)}$$

When $\dot{W}$, V, F_{roll} are obtained through testing or are known, F_{drag} can be determined by the following equation:

$$F_{drag} = \dot{W}(0.95/V) - F_{roll} \qquad \text{eq (5.6)}$$

Knowing the drag force acting on the cyclist and knowing A, V, ρ for a given test condition, using equation (5.3), C_d is the following:

$$C_d = F_{drag}/(\rho(V^2)A/2) \qquad \text{eq (5.7)}$$

Kyle studies indicate that there is no significant change in C_d for a given configuration.

Typical Values for Thesis Test Cyclist

The following values are based data obtained from previous research, they are presented here as information for the reader in which to compare actual test data collected by the author. A description of the test cyclist can be found in chapter 4 of this thesis, under the heading of Test Cyclist.

Based on data collected from the Nonweiler wind tunnel studies the test cyclist should have a frontal area of 3.15 and 3.3 ft^2. Whitt studies have determined an approximate frontal area of 3.65 ft^2. There is no significant change in frontal area with increasing cyclist speed, (Nonweiler).

At 30 mph a Cannondale bicycle similar to the bicycle tested for this thesis which was an aluminum frame, 36 round spoke 27 inch wheels (author's bike had 700 mm wheels), drag results for the bicycle was 2.72 lb, 7.25 lb for the bicycle plus rider . For a weight of cyclist plus bike of 170 lb riding in the racing position at 20 mph on a flat windless course the power required was 0.21 hp or

160 watts, (Whitt, 1990). For a typical cyclist in the racing position, weighing 158 lb, and using a lightweight racing frame, the following has been extrapolated from Kyle May 1988 study, figure 3 of the report:

Kyle's Power Required for a Cyclist at Given Speeds

Speed (mph)	Horsepower	Power (ft-lb/sec)	Power Output (watts)
10	.075	41.25	55.95
15	.129	70.95	96.20
20	.214	117.70	159.58
25	.336	184.80	250.56
30	.514	282.70	383.29

According to Sharp page 241, rolling resistance forces are one thousandth of the weight of the rider. Rolling resistance for a 150 rider and a 30 lb bicycle has an incremental rolling resistance coefficient of 0.001.

Chapter 4

Description of Test Equipment

Clip-on Aerobars

Clip-on aerobars are available from several different distributors. They were originally used in a primitive form by Pete Penseyres during his 1986 record breaking Race Across America (RAAM) time of 8 days, 9 hours, and 47 minutes. The resting pads provided Penseyres with an alternate position for him to rest his arms during the hours and days of continuous cycling. It was later discovered that use of simple clip-on extensions to a regular pair of handlebars could significantly reduce a riders cross-sectional area, and as a result decrease the amount of pressure drag, thus increasing his or her speed.

The aerobars used for this test were manufactured by Profile Incorporated, Chicago, Ill. The bars weight 485 gm and retail for around $65. The advantage that the Profile clipon's have over other brands on the market is their ability to be adjusted fore and aft and to some extent in height. The handlebars come in three different widths; six, eight, and nine inches. The clip-on handlebars are clamped onto the regular handlebars and can easily installed and adjusted by the cyclist for correct fit in about ten minutes. For testing purposes the aerobars were set at angle of +20 degrees from level. A photograph of the author using the aero-bars is presented in appendix B, figure 1.

Back Wheel Disk Cover

A back wheel disk cover is a "Poorman's" disk wheel. Unlike a disk wheel which is a solid structure resembling a disk, the disk cover fits over the existing back wheel through a series of plastic clips that are attached to the the wheel spokes. Although tested on the front wheel, its use on the front wheel is not recommended due to controllability problems in crosswinds discussed earlier. This simple, but effective concept has gone through several interations over a five year period.

The latest version tested was the Stealth Titanium, manufactured by UNI-USA, of Aloha, OR and is comprised of rubber bonded fabric is stretched over two light titanium hoops. It comes in two disks, one for each side of the back wheel and weights 238 gm and retails for $64.95. The set is delivered to the owner in a pizza box and construction takes one and one half hours to complete. Once installed the disk cover can easily be taken on and off or reinstalled in a few minutes. A photograph of the author using the back wheel disk cover is presented in appendix B, figure 2.

Tri-Spoke Wheel

The tri-spoke wheel is a variation of the disk wheel with the structure modified to three large spokes. There are also five-spoked wheels on the market. The wheels were originally developed as an alternative to the standard front-spoked wheel. As discussed previously, front wheels are usually not solid because of instability problems in crosswinds. The tri-spoke and five-spoke wheels are constructed of composite material. The spokes on the tri-wheel consists of three identical symmetrical airfoil cross sections. Some research has indicated that during crosswind conditions, the airfoil cross sections experience "lift" and therefore provide the cyclist with some additional forward momentum. These wheels are costly and not designed for everyday use.

The tri-spoke front wheel tested is a Zipp 3000 manufactured by Allstop Corporation of Indianapolis, IN. It is a full composite material of unidirectional carbon fiber and woven Kevlar. The tri-spoke wheel has an all-composite rim that is not designed for constant breaking wear. The Zipp 3000 weighs 900 gm and retails for $885. It is easily installed in seconds using a lightweight quick release. A photograph of a cyclist using the Zipp 3000 is presented in appendix B, figure 3.

Aero Fairing

Aero fairings installed on the front of the bicycle have been around for about six years. Earlier, more rustic designs were tested since the 1920's, Whitt, 1990. The fairing resembles that seen on motorcycles. In fact, during my ride across the country my bike was mistaken several times for a motorcycle. Another advantage of aero-fairings is limited protection from the wind, weather, and bugs. Also, during tailwinds it acts like a spinnaker on a sailboat and helps propel the cyclist forward.

The aero fairing evaluated was the Breeze Cheater manufactured by Fairfield Product Engineering Corp of Fairfield, CT. It is constructed of several layers of Kevlar and has a gellcoat finish. The windshield is constructed of clear polycarbon. The fairing, which is attached to the bike using steel and aluminum hardware, requires about two hours to assemble. The Breeze Cheater weighs about three lbs and retails for $250. The fairing can be installed or removed in about five minutes. A photograph of the author using the aero fairing is presented in figure appendix B, 4.

Clothing

Cycling shorts made of Lycra are fairly standard and have been around for years. Lycra fabric clings to the cyclists body which provides some aerodynamic advantage. Lycra shorts are available in every conceivable style and color and usually have a pad inside that allows the rider a little more comfort on long rides. Cycling jerseys are made of several different types of material and usually have three pockets in the back so the cyclist can carry some food, keys, or water bottles. Tight fitting cycling clothing is comfortable and can significantly reduce drag when compared to regular, loose fitting, athletic wear. Cycling jackets are designed specifically for riding during adverse weather conditions.

The cycling jerseys worn for this test were made of Coolmax material that allows perspiration to be wicked away from the body and fit the rider snugly. The jacket is designed to be practical, not necessarily tight fitting and therefore was evaluated to determine the aerodynamic affects of loose fitting clothing. Cycling shorts were manufactured by Performance Bicycle Shops, of Chapel Hill, NC and retail for $40. The cycling jerseys were made by Carolo, of Miami, FL and was designed specifically for the rider. The cycling jacket was manufactured by Burley of Eugene, OR and retails for $85. A photograph of a cyclist wearing the Burley jacket is presented in appendix B, figure 5. The cycling shorts and jersey can be seen in all other photographs.

Bicycle

Bicycles vary considerably in weight and components. Prices can range from a low-end model costing a couple hundred dollars to custom made bicycles designed specifically for the owner's dimensions and specifications costing upwards of ten thousand dollars. A medium price range for a fairly light bicycle with mid-range components is from 400 to 800 dollars. Today's bicycles are constructed from over 1000 separate components.

The bicycle used for this test was the Black Lightening manufactured by Cannondale Corporation of Georgetown, CT. The bicycle had 21 gears and was design for racing. The frame was constructed of arc welded aluminum tubing and weighs approximately three lbs. The complete bicycle has a test weight of just under 23 lb. Water bottles racks are constructed of composite fiber. Rims are constructed of annondized aluminum and were comprised of 36 spokes per rim. Tires were clinchers or tires that require the use of an innertube and utilized a Kevlar belt and bead for lightness and durability. Tire diameters on both were 20 mm. Total cost of the complete bike was approximately $800. Standard racing handlebars were used. A photograph of the author on his bicycle in the racing (baseline) position is presented in appendix B, figure 6.

The touring and aero combination configurations tested are presented in appendix B, figures 7 and 8, respectively. A summary of the equipment tested is presented in appendix A, table 1.

Test Cyclist

The test cyclist and author is 29 years old and has averaged over 5000 cycling miles per year from 1988 through 1992. He has bicycled through Australia and across the United States. The test subjects anthropometric measurements are presented in appendix A, table 2. The average weight of the author during his ride across America was 155 lbs. The cyclist's weight for the post-BAA test periods averaged 158 lb.

Test Instrumentation

There were several pieces of test instrumentation that were used during the testing. A 50 lb Digital Force Gage manufactured by Dillon Weigh-Tronics was used to measure rolling forces and to weigh various components. The force gage was calibrated to the nearest tenth of a lb and was last calibrated December 13, 1991.

A standard stopwatch accurate to one hundredth of a second was used to record data runs. The stopwatch was manufactured by Timex. The stopwatch was mounted next to the cyclocomputer on the bicycle handlebars. There is no known calibration date.

A wind measuring set, number AN/PMQ-3A, was used to measure local wind conditions around the test courses. This anemometer was manufactured by The Instrumentation Corporation of Baltimore, MD. The unit was last calibrated on April 11, 1989. The anemometer provides wind speeds in knots using two scales. The first scale, 0 to 60 kt, is for strong winds and the second scale, 0 to 15 knots is for light winds. The direction of the wind is also determined by a spinning windvane on top. The anemometer was accurate within half a knot.

A Cateye Micro cyclocomputer, model number CC-6000, was used to record a majority of the test parameters. The cyclocomputer was manufactured by Tsuyama Manufacturing Corporation of Japan. The unit was calibrated by the manufacturer prior to shipment in December 1990. The calibration was verified with other brands of cyclocomputers during 3566 mile ride across America and was determined to be accurate for the purpose of these tests. The unit is comprised of two magnetic pickups; one located on the rear wheel and a second pickup mounted on the left pedal. The cyclocomputer was used to indicate stable conditions to the cyclist and whether or not pedal rpm was on condition. The following data and tolerances indicated below were obtained during testing:

Cyclocomputer Test Parameters

Parameter	Tolerance
Distance	hundreth of a mile
Average Speed	tenth of a mph
Time	nearest second
Maximum Speed	nearest mph
Odometer	tenth of a miles
Pedal Revolutions	nearest rpm

Chapter 5

Description of Test Techniques

Testing While Bicycling Across America

The test course was 3566 miles long during and traversed the United States during 47 days of cycling, averaging 90 to 100 miles a day. The author represented a typical cyclist using the aerodynamic components over a wide range of adverse terrain and environmental conditions which would been difficult to simulate in any other way. The ride began and ended at sea level but included climbs totaling over 65,000 feet in elevation, with a comparable loss in elevation. The aero equipment evaluated were the aero fairing, the disk wheel cover, and the aerobars. The terrain varied from desert, to mountains, and to rolling plains. Winds were predominantly tailwinds from 090 to 270 degrees with respect to the front of the bicycle but equipment was evaluated in crosswinds in excess of 55 mph. This phase of the evaluation was qualitative in nature due to the varying of terrain and weather conditions.

Handling qualities of the aero components as well as accelerated reliability were evaluated during the 47 day trip. It is estimated the miles and conditions tested represented three years of normal use. In addition, other types of aerobars, bicycles, and components were evaluated by other cyclists on the ride and their comments are included in this thesis as additional supporting data. The handling qualities of the aerodynamic equipment is important because poor ergonomics can nullify the aerodynamic advantage of the components.

During long mountain descents the maximum velocity attained was recorded without pedaling while the cyclist assumed the aero fairing position. This position was: elbows bent and underneath shoulders and chest, body and head behind the aero fairing, knees pointed in and hugging the top tube. The author's coastdown was compared to other cyclists of similar weight and build in side by side descents. Other cyclist were in one of the following: racing position, deep tuck position, or using aerobars. Additional pedaling to spinout or maximum velocity as possible using highest gearing ratio was also assessed. Handling qualities during high speed descents were quantitatively evaluated.

Coastdown Tests

Coastdown tests were conducted on St. Mary's County Airport Road near California, MD, on 5 and 26 October 1991. The course length was 0.3 miles. A decline of approximately 14 degrees extended from the course starting point to 396 ft. From 396 ft to 1573 ft the course was flat with less than one foot change in altitude. Data runs were initiated from the top of the hill from a dead stop, a straight line was maintained throughout the run until speed decreased to 3 mph. The 3 mph stopping speed was utilized as a result of bicycle handling quality and stability problems at speeds less than 3 mph. Since testing was conducted in the local area of NAS Patuxent River, MD, the base weather station data was recorded before and after each testing phase. Runs were conducted under the following atmospheric conditions:

Pressure = 30.20 to 30.4 in of Mercury.
Temperature = 59 to 73 degrees F.
Relative Humidity = 83 to 93 %.

Testing was conducted during the first two to three hours proceeding sunrise to minimize any possible wind effects. Winds were calm during testing. If a breeze was registered testing ceased. The configurations evaluated were compared to the racing position baseline. Once speed was reduced to 3 mph brakes were immediately applied, and data stopped and recorded. Positions were marked on the road along with the corresponding run number and were measured upon the completion of the days testing. Each configuration was tested up to four times to confirm repeatability of data. The following configurations were evaluated:

Coastdown Configurations

Number	Configuration
1	Racing Position (Baseline)
2	Touring Position
3	Aerobar
4	Back Wheel Disk Cover
5	Tri-spoke Front Wheel
6	Aero Fairing
7	Combination of 1,3,4,5
8	Cycling Jacket

Rolling Resistance Test

Rolling resistance tests were conducted to determine the rolling force component of the wheels on the road. Tests were conducted in order to better isolate the importance of tire inflation and overall effects with changing speed. The test cyclist was towed by a car at speeds up to 20 mph, on a level road with a representative blacktop surface from a stiff rope. One end of the rope was connected to the bicycle via a hook and the other end was connected to a digital force gage. When the cyclist was stable and there was no slack in the rope data was recorded. Two identical sets of tests were conducted with the exception that tire pressure was varied between the two series of tests. The first series of test were conducted with a tire pressure of 100 psi in both tires. The tires were then deflated to 80 psi and the series of tests were repeated. The 80 psi test was conducted to investigate a cyclist with an under inflated tire and how this would affect the rolling force.

Level, Constant RPM Test

Constant RPM tests were conducted on Saufley Road, located on NAS Patuxent River. The total course length was 0.6 miles on standard blacktop with changes in elevation less than one ft per quarter mile. Data were collected during five test periods from 19 through 26 October 1991. Since testing was conducted on NAS Patuxent River, MD, the base weather station data was recorded before and after each testing phase. Runs were conducted under the following atmospheric conditions:

Pressure = 29.98 to 30.28 in of Mercury.
Temperature = 60 to 70 degrees F.
Relative Humidity = 60 to 90 %.

The evaluation was conducted during low wind days of less than two knots typically within two hours after dawn or before sunset. As soon as a breeze was registered testing ceased. The racing baseline configuration was evaluated during each test period under different gearing ratios and corresponding velocities to verify repeatability of data. Helicopter low-airspeed techniques over a measured course were utilized for this evaluation. Runs were conducted on reciprocal headings then averaged to cancel out any possible terrain or wind effects. The cyclist would stabilized on condition at 90 rpm (within1 rpm) prior to initiation of data run. Any runs that that were not stable over the 0.25 mile test distance were repeated. The 0.25 mile course was used for four different power settings. Once 0.25 mark was indicated on cyclometer, instrumentation was stopped and data recorded. The following configurations were evaluated:

Level, Constant RPM Configurations

Number	Configuration
1	Racing Position (Baseline)
2	Touring Position
3	Aerobar
4	Back Wheel Disk Cover
5	Tri-spoke Front Wheel
6	Aero Fairing
7	Combination of 1,3,4,5
8	Cycling Jacket

The higher power setting tested, with a gearing ratio of 52 to 13, resulted in a baseline speed of approximately 26.5 mph. This data was stabilized for 0.1 miles as a result of the difficulty for the cyclist to remain on condition at this speed. As with the four lower power settings, data were validated for repeatability. The touring position and the cycling jacket configurations were not conducted at the higher power setting because it is not likely that a cyclist would use these configurations at higher speeds.

Frontal Area Study

The frontal areas of each test configuration were determined in order to calculate a corresponding drag coefficient, C_d. Since this is usually determined during wind tunnel tests, the author improvised a setup by which to approximate the frontal area, A. The setup included a video camera, a monitor, graph paper and measurements of known distances. The cyclist mounted the bicycle and was recorded on video tape facing head on. The camera was 17 ft away from a reference plane defined by the front wheel hub and the brake hoods. The width of the bicycles handlebars was a known distance of 16 in. The author then placed of piece of transparent graph paper on the monitor with graduations of 10X10 squares per half inch.

The conversion scale between the graph paper and the cyclist was four inches cyclist length equal to one half inch on the graph paper and monitor. Using this conversion scale, the handlebars, via the monitor, were lined up with graduations of the paper and the video camera was verified to be in position. The configuration was then filmed, played back, and frozen at the data point. The image was then traced on graph paper and the approximate frontal area in inches was then calculated for each condition.

Side views of the configurations were also recorded using the distance between the center of the rear derailer and the center of the pedal as the reference for a length of 16 inches. The bicycle was located 20 ft from the video camera. This distance of 16 inches and corresponds to the graph paper as four in of bicycle length equal to on half in on the graph paper. The side views were recorded for possible use in future studies.

Chapter 6

Results

Bicycling Across America Results

When the author started the ride, his aerobars were not adjusted properly, the clipons were too short. This was pointed out to the author by another rider who had a similar problem when he first installed his set of Profile clipons. Throughout the ride, the author fine tuned the distance until he found the best compromise between comfort and aerodynamic performance. The position used for the tests was the following: the aerobars at an angle 15 degrees above level, the length was nine inches from the attachment point to the front grip. This allowed the author to rest his arms with his elbows just touching the end of the pads. The width of the aerobars was 8 inches which allowed the cyclist comfort but still brought the authors elbows in underneath his chest. The positioning of the aerobars was based on the research conducted prior the ride and resulted in an optimized aerodynamic profile. During long and short ascents the additional weight of the aerobars was not noticeable.

Several riders used a different brand of aerobars produced by Scott. Of the ten riders interviewed, two used the Scott bars throughout the ride, six rarely used the bars, and two removed the bars half way through the ride, or around Kansas. The most cited reason for not using the Scott bars was the discomfort of the bars. The Scott bars were not adjustable to the riders dimensions and were six inches wide. Of the cyclists interviewed who purchased Profile aerobars, most used the bars during BAA on a regular basis. The author's decision to purchase the Profile clipon bars instead of the Scott bars for the ride was because the Profile bars were adjustable and came in three different widths.

The aerobars were best used during straight, flat or descending runs. When the course had curves or when quick reaction was required, use of the aerobars was difficult and dangerous. Using aerobars, the cyclist looses sensitivity to the turns and has a tendency to overcompensate. At speeds in excess of 25 mph, a cyclist can easily become unstable when required to maneuver rapidly to avoid a road hazard. Steering with the aerobars is difficult because the cyclist ends up using his whole upper body, as compared to a rider in the racing position who leans into turns and makes subtle corrections with his wrist and arms.

The back disk wheel cover worked well. There were no problems with crosswinds. Initial qualitative test runs over a 18 mile course prior to BAA, showed an increase in speed of one to two mph as compared without the wheel cover. The crosswinds were not a problem due to the amount of weight distributed on the back wheel and the fact that the back wheel only moved in the plane of the frame. During climbing the extra weight of the disk cover was not noticeable.

The aerofairing operated well under tailwind and no wind conditions. With rear cornering winds the fairing acted much like a Spinnaker sail and would pull the bike along. When outside air temperatures were in excess of 100 degrees F through the California and Arizona desert the fairing reduced the amount of cooling wind and hampered the cyclist's performance. On steep descents of several thousand feet a maximum speed of 40 mph was attained when tucked behind the fairing, and not pedaling. This data point was repeatable. At 40 mph, the plexiglass would bend back two inches from its normal position. Riders of comparable weight and size in a full tuck position would pass the author on descents. When pedaling to "spinout," using a maximum gear ratio of four, the author could maintain 52 mph on long descents in excess of 750 ft in altitude. Spinout is the condition where using the maximum gearing ratio on the bicycle the rider can no longer add additional power to the system no matter how fast his rpm rate.

There were several days where the crosswinds were in excess of 50 mph. During these conditions the aerofairing was difficult to maintain on the desired heading. The side forces on the surface of the fairing were significant. To compensate for the side forces applied to the fairing during 50 mph crosswind, the cyclist had to lean 5 to 10 degrees into the wind. While climbing, the aerofairing three pound weight was significant. The additional weight fatigued the rider when compared to similar ascents without the fairing.

While cycling with the aero fairing, back wheel cover, and aerobars at the Major Taylor Velodrome in Indianapolis, IN, speeds of 25 to 28 mph could easily be maintained using a gear ratio of four.

Coastdown Test

Coastdown results were repeatable and data were processed using the Excel spreadsheet program. The data were not affected by changes in weather within the ranges presented in chapter 5. A list of tabularized results is presented in appendix A, table 3. A graph of the final results is presented in appendix B, figure 9. As expected, the touring position and the cycling jacket configurations were slower than the racing position baseline. The slowest configuration was that of the cyclist upright in the touring position, which had a distance traveled of 1204 ft in 81 sec. The greatest benefit was achieved by the clip on aerobars with a distance using this configuration of 1489 feet and a run time of 104 sec. This was only surpassed by the aero combination configuration which had a distance of 1563 ft and a run time of 104 sec.

The coastdown tests were conducted prior to any other testing and the results were useful when correlating with data from other tests. This type of testing can only be conducted during conditions were there is no wind, and even a wind of one to two knots was significant enough to invalidate the data. Data runs conducted in slight intermittent winds were erroneous and therefore were thrown out. Coastdown testing is a valuable method to evaluate individual component configurations.

Rolling Resistance Test

The rolling resistance test were repeatable and did not vary for the speed range tested of 0 to 20 mph. Previous research indicated a rolling resistance force of 0.8 to 0.9 lbf was to be anticipated for the given conditions. For a cyclist and bicycle combined weight of 181 lb, and a tire pressure of 100 psi, the rolling force averaged 0.8 lbf. For the same cyclist and bicycle with a tire pressure of 80 psi, the rolling force averaged 0.9 lbf. It is assumed for speeds greater than 20 mph the rolling forces would be the same for the conditions presented above. Data obtained during rolling resistance testing correlated favorably with results from other studies researched.

Level, Constant RPM Test

Level, constant rpm results were repeatable and data were processed using the Excel spreadsheet program. All the results were compared to the baseline racing configuration which was repeated during each series of evaluations to validate the results tested on different days. Within the range of conditions presented in chapter 5 under level, constant rpm test, the repeated data points did not vary with changes in weather. A list of tabularized results is presented in appendix A, table 4. Graphs of each configuration as compared to the change in racing baseline are presented in appendix B, figures 10 through 16.

The curves for each configuration are presented as time saved or lost when compared to the baseline racing configuration. The baseline data is represented by the x-axis. The solid lines on the plots indicate regions defined by data points tested. The dashed lines are extrapolated data. As with the coastdown tests, the touring position and the cycling jacket configurations were slower than the racing position baseline.

The most disappointing results were that of the tri-spoke front wheel, considering the article cost $885 dollars. There were was no appreciable increases in time saved using this item, although it may give its rider a certain psychological advantage. The wheel felt out of true as if it were not balanced correctly. Unfortunately this is not an easy problem to correct. For a standard spoked wheel all the cyclist has to do is find a spoke wrench and tune the wheel back into its correct shape. With the tri-spoke wheel, the owner would most likely have to send the rim back to the manufacturer. The manufacturer would then add material where appropriate to balance the rim. This would result in additional weight to this component.

The sidewalls of the tri-spoke wheel were also made of composite material and could not be used for much braking because the rims wore quickly when the brakes were applied. The current composite rims on the market have solved this problem by adding an aluminum braking area.

Frontal Area Test

The frontal area test data are presented in appendix A, table 5. This evaluation was conducted with some degree of success, although it was determined that not all the configurations could be estimated using this method. The aerofairing frontal area could not be accurately estimated due to the complexity of the three dimensional surface preceding the reference plane. The areas of the disk wheel covers and the tri-spoke wheel were difficult to determine due to the small change in the frontal area when compared to the baseline or racing configuration. As a result of the inability to accurately determine the tri-spoke and disk wheel cover frontal areas, the author did not approximate the frontal areas for the aero combination configurations. Therefore, the frontal areas for configurations 4 and 5 presented in appendix A, table 5, are rough approximations based on the results of the coastdown and level constant rpm studies. The frontal areas were included here to provide the reader with some reference to the approximate frontal areas. Follow-on testing conducted in a low speed wind tunnel would be the best way to determine actual frontal areas for each condition.

Based on the results of previous wind tunnel research presented in chapter 3 of this thesis, the frontal areas for configurations 1, 2, 3, and 8 appear to be reasonable. Initially, the author wanted to use a calibrated back wheel developed by Look Incorporated to determine the power required for each test configuration at various speeds, but the instrumentation was unavailable during testing. As a result, the data collected from Kyle's 1988 wind tunnel study was used for power required. The data presented is for a cyclist weighing 158 pounds using a lightweight racing bicycle in the baseline racing position traveling at 30 mph. The approximate values for Cd can then be determined for the various configurations. These values are presented in table 5.

Chapter 7

Conclusions and Discussion

General

The two major test, Coastdown and Level Constant RPM, were conducted as a result of literature research which indicated these tests were second only to wind tunnel testing. The two major tests compared favorably with prior wind tunnel results. The supporting tests were the rolling resistance study to confirm previous tests and the frontal area study. The frontal area study was an evolution by the author based on the tactics used by various syndicates in the America's Cup 1992 sailing campaigns to evaluate competitor's boats. Using the techniques developed and utilized in this thesis, the author now has the capability to study several different types of human powered vehicles. This study can also be customized for any cyclist that might wish to improve his or her aerodynamic efficiency.

Time Saved or Lost

Data were generalized and compared for each configuration at three representative speeds; 20, 25, and 30 mph. The choice of these speeds was a result of the author's experience which indicates most cyclists typically fall into one of these three average speed categories for a 25 mile course. If information was provided at only one speed like several resources in the bibliography, then cyclists at the other performance levels would find it difficult to use the results of this study. Most cyclist, even at the professional level, cannot maintain average speeds much faster than 30 mph on a level course. The data is presented in tabulated form in appendix A, tables 6, 7, and 8. Time saved or lost when using one the configurations tested at 20, 25, and 30 mph are presented in appendix B, figure 17.

Cost Per Second Saved

These tests have proven the cost of the aero components is not proportional to a time savings. The cost versus time savings for the configurations at 20, 25, and 30 mph are presented in appendix A, tables 6, 7, and 8. A generalized plot of the tabularized results is presented in appendix B, figure 18. The most effective aero component was also the least expensive, which was the clipon aerobar at a retail cost of $65. With the exception of the aero combination, the aerobar saved the most time and had the best cost per second ratio (44 cents/sec) at 25 mph of all the components tested. The aero combination results indicate the time savings of the individual aero components are not additive when used together. Although not tested, the most effective cost to time savings ratio would probably be a combination of the back wheel disk cover and the aerobars. Modifying the cyclists riding position can significantly save time without purchasing any aero components.

Tri-Spoke Wheel

The results of the Coastdown and Level Constant RPM tests compared favorably in each case with the exception of the tri-spoke front wheel. Coastdown tests indicated that the tri-spoke front wheel should have been faster than the back wheel disk cover. For the level tests this was not the case, as the back disk wheel cover was consistently faster than the tri-spoke wheel.

The poor performance of the tri-spoke front wheel may be the result of several factors. First, the tri-spoke with a weight of two pounds is about a half a pound heavier than the standard 36 spoked front wheel used in the other configurations. This would provide the tri-spoked wheel with more inertia during the sloped runs when compared to a regular 36 spoked wheel. Second, using the tri-spoke wheel at speeds in excess of five miles per hour resulted in an impression by the author that the wheel was slightly out of round. Although the sleek appearance of the tri-spoke wheel's structure was impressive, its performance indicates some flaws in the manufacturing process. Third, even minimal braking wore the composite rims each time the brakes were applied.

Other composite spoke manufacturers have solved the rim wearing problem by gluing an aluminum ring to the exterior of the composite structure. The ring resembles the outside of a standard bicycle wheel rim and saves the composite from absorbing the brake friction. The thumping or out of round condition could have been a result of the additional weight of the inner-tube stem inside one of the three spokes. Several manufacturers have addressed this problem by favoring a quad-spoke design over a tri-spoke.

There are several advantages of the quad-spoke over the tri-spoke configuration. Each quad-spoke can have a smaller cross-sectional area. The spoke opposite the stem can be weighted or balanced to minimize the effects of the valve stem. Construction of a composite structure offset 90 deg is usually simpler than the 120 deg structure of a tri-spoke wheel. The wheel forces are better distributed over four spokes than with three.

Aero Fairing

The aero fairing results although favorable could be improved upon. Using the aerobar with the fairing installed results in the cyclists unable to maintain the low profile of the aerobar configuration. This is due to the height of the plexiglass windscreen. The author was uncomfortable viewing through the plexiglass. It is recommended that if the aerofairing is to be used in conjunction with aerobars that the wind screen be trimmed four to eight inches depending on the cyclist's height and personal riding style.

The secondary advantage of reducing the size of the windscreen is that the frontal area is also reduced. It should be remembered that front aerodynamic fairings like the one tested are not legal under current ICU regulations. But for a cyclist who is looking for personal improvement or a piece a equipment that can keep the wind chill off him during cold rides, the aero fairing could be the answer.

Cycling Jacket

A cyclist in the racing position saves over a minute and a half during a 25 mile ride over the same rider using the touring position. Also, wearing a jacket, even like the relatively tight fitting cycling jacket tested, will significantly increase a cyclist's drag. A jacket can also overheat or chill a cyclist even on cooler days because most jackets do not allow moisture to escape. Professional cyclist solve this problem by wearing long sleeved jerseys or arm and leg warmers on cold days around 30 deg F. On high mountain descents cyclist in the Tour De France use newspaper between their skin and their jersey to act as a barrier. At the end of the long cool run they throw the paper way.

Lessons Learned, Ways to Improve Future Evaluations

Based on what the author has learned from conducting this study, there are several ways to improve the testing to obtain accurate results in a shorter amount of time. The author initially conducted the level constant rpm tests on a one mile course. It was difficult for the cyclist to maintain a stable data point due to automobile traffic and slightly rolling road surfaces. The final course on Saufley road was utilized because of the minimal amount of traffic during the periods tested and the relative flatness and uniformity of the road surface.

The Look Incorporated Calibrated Wheel hub should be utilized for future test because it provides power required output data along with several other additional parameters that would have been valuable to the author to simplify data analysis. The Look calibrated wheel was unavailable to the author during this evaluation. The power required would also be available as test data so that studies could be conducted on several different size and type of cyclist.

Although data did not vary within the weather conditions tested, further tests could be conducted during hot and cold extreme conditions and at various altitudes to verify the correlation of the data.

Optimizing seat and handlebar heights is one of the most effective and cheapest ways of increasing aerodynamically efficiency. Future testing can be conducted varying the handlebar height in relation to the seat height for a group of cyclist.

Further study could also be conducted on individual components such as water carrying devices, bicycle helmets and the modification of the bicycle frame through fairing of the brake and derailer components.

Chapter 8

Applications of Test Results to Other Low Speed Vehicles

Human Powered Vehicles

General

Major advances in the development of human powered vehicles have occurred since Paul MacCready won the Kremer Prize for controlled human flight in 1977. He won it through the ingenious use of materials available to him. Upon perfecting his design, everyone on his design team was eventually allowed to take a chance flying the Gossamer Condor. What MacCready had done is refine his design to the point where non athletes could lift the craft into the air. Developing vehicles for use by non athletes is required for human powered vehicles to be successfully incorporated into our everyday life.

The vehicles must be designed to be propelled by ordinary people with relatively sedentary lifestyles. This requires refinement of the design through the use of fairings and other aerodynamically enhancing devices to increase the vehicles speed for the same power input to the system. The testing conducted for this thesis allowed the author to take important steps by obtaining knowledge through the aerodynamic refinement of a fairly simple vehicle, the bicycle. The techniques used in this evaluation could be applied to any form of human propelled machine be it a commuter vehicle, wheel chair, an airplane, a helicopter, or a submarine. The advantage of such human powered designs is that the vehicles are non polluting, relatively safe to operate, and provide the user with physical activity that may not be acquired any other way.

Commuter Vehicles

Commuter vehicles of all sorts are now being designed by engineers and tinkerers around the world. The general public, although interested, will not use these vehicles unless the machines meet the following requirements: able to achieve speeds in excess of 40 mph with minimal amount of effort, protection from the elements, and cost effectiveness. This thesis has studied to some degree these three areas.

By reducing the frontal area of the cyclist it has been shown that faster speeds can be obtained for the same amount of power at a given condition. Additions to the bicycle frame such as the aero fairing not only reduce drag but provide the user a degree of protection from wind and rain. The relative cost of the additional aerodynamically enhancing devices to improve vehicle performance are fairly inexpensive. The author has gained experience on this basic level and plans to develop and improve designs for the commuter vehicles for the future.

The author envisions human powered commuter vehicles to be the way of the future for some areas of the country. Ninety percent of workers in America live within ten miles of their place of employment. Insurance of these vehicles and their independence from oil or electric power, combined with the country's growing concern over environmental pollution and health related issues point to this solution to be extremely viable. Human powered commuter vehicles offer a cheap alternative for most workers in the country.

Wheel Chairs

With the growing concern for the physically challenged sector of our population, the wheel chair could be refined using the techniques presented in this thesis. Wheel chair races are gaining popularity with marathon and other related events. A test program applying the techniques used in this thesis could lead to improved aerodynamic design for wheel chairs. This would result in greater mobility and freedom for this segment of the population. The author could develop a test program to evaluate and modify existing bicycle components to be incorporated in the design of new, faster, wheel chairs.

Human Powered Airplanes

The techniques evaluated and designed in this thesis are similar to those used in developing the first successful controlled flight of a human powered aircraft. Even though this vehicle had a forward velocity of 10 to 15 mph when aloft, the fairing of the cyclist compartment was critical to the success of the design. The information learned by shielding of cables and wires, similar to brake and gearing cables and wheel spokes on a bicycle, could be applied to refine these designs even further.

Human Powered Helicopters

Sporadic work has been done in the area of human powered helicopters with some success. The two most advanced designs were built several years ago by students from the California Polytechnic Institute and the Massachusetts Institute of Technology. The author had the opportunity to examine the California Polytechnic Institute craft and talk to some of the students involved in the project. Although their design was impressive, it could be improved by adapting the techniques evaluated in this thesis.

The cockpit area of the vehicle could be faired such that the disturbance of the airflow around the pilot could be minimized. Also, the size and stature of the cyclist could be evaluated based on the proportional power output in order to optimize the tradeoffs between weight and drag drag.

Human Powered Submarines

Each year there are several sponsored contests at the collegiate level for human powered submarines. Once again the techniques used in this thesis would apply here. The major difference between a bicycle and a human powered submarine is the fluid in which the vehicle operates. Although a coastdown test would not be effective, unless conducted vertically in a large column of water, the level constant speed tests used in this thesis could be modified for underwater testing. By modifying the fairings surrounding the pilot methodically during successive runs, an optimal configuration can be obtained.

Low Speed Aircraft

Ultralight Aircraft

Ultralight aircraft designs are usually more functional than aerodynamic. Most ultralight aircraft have exposed cables, pilots and powerplants. Since the size of the vehicle many time limits the weight of the engine, performance improvements could be made using the techniques applied in this evaluation. Cables could be rerouted when possible inside wing and tail boom sections and when not possible, cables with an elliptical cross sections could be used to minimize wire drag. The engine and pilot could be faired using similar materials as the aerofairing evaluated. The pilot frontal area could be reduced by designing a more reclined position.

Helicopters

Military helicopters characteristically are not optimized to reduce drag. The helicopter appears to be designed more for utility than efficiency. The new light helicopter for the Army, the Commanche, may be a step in the right direction with its recessed store carrying capability and its smooth aerodynamic profile. The knowledge developed during this thesis will allow the author in the future to approach the use and design of external stores and components from a fresh perspective. The author has worked and designed several external stores in the past and will now take this new knowledge and apply it to future design projects.

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APPENDICIES

Table 1

SUMMARY OF TEST EQUIPMENT

EQUIPMENT	PRODUCT NAME	MANUFACTURER	INSTALL TIME	WEIGHT	COST ($)
CLIP-ON AEROBAR	PROFILE CLIP-ONS	PROFILE	10 MINUTES	1 LB 1 OZ	65
BACK WHEEL DISK COVER	UNI TITANIUM	UNI-USA	2 MINUTES	8.4 OZ	64.95
AERO FAIRING	BREEZE CHEATER	FAIRFIELD ENGINEERING	5 MINUTES	3 LB	250
TRI-SPOKE WHEEL	ZIPP 3000	ZIPP	15 SECONDS	2 LB	885
CYCLING JACKET	CYCLING JACKET	BURLEY	1 MINUTE	10 OZ	85
BICYCLE	BLACK LIGHTENING	CANNONDALE	- -	23 LB	800

Table 2
ANTHROPOMETRIC DATA

Dimension	Measurement	Percentile (1)
Weight	158 lb	24
Stature	67.9 in	15
Sitting Height	36.7 in	65
Sitting - Eye Height	32.3 in	75
Functional Reach	31.2 in	45
Trunck Height	26.1 in	98
Shoulder Width	18.2 in	25
Buttock to Knee	22.0 in	2
Buttock to Leg	41.5 in	- -

Note: (1) Anthropometry of Naval Aviators, 1964.

Table 3
COASTDOWN DATA RESULTS

TEST NUMBER	CONFIGURATION	TIME OF RUN (MIN.SEC)	DISTANCE TRAVELED (FT)	AVERAGE SPEED (MPH)	MAXIMUM SPEED (MPH)
1	Racing Position (Baseline)	1.23	1277	12	19
2	Touring Position	1.21	1204	11	19
3	Aerobar	1.44	1489	12	20
4	Back Wheel Disk Cover	1.25	1290	12	19
5	Tri-spoke Front Wheel	1.27	1342	12	20
6	Aero Fairing	1.30	1427	12	20
7	Aero Combination (1,3,4,5)	1.44	1563	12	20
8	Cycling Jacket	1.23	1249	12	19

Table 4

LEVEL, CONSTANT RPM SPEED RESULTS

TEST NUMBER	(1) CONFIGURATION	MPH	MPH	MPH	MPH	MPH
1	**Racing Position (Baseline)**	**10.00**	**15.00**	**20.00**	**25.00**	**30.00**
2	Touring Position	9.98	14.91	19.74	24.37	28.73
3	Aerobar	10.05	15.18	20.49	26.08	32.11
4	Back Wheel Disk Cover	10.02	15.06	20.16	25.33	30.60
5	Tri-spoke Front Wheel	10.02	15.05	20.12	25.22	30.35
6	Aero Fairing	10.03	15.12	20.30	25.61	31.10
7	Aero Combination (1,3,4,5)	10.07	15.23	20.58	26.21	32.22
8	Cycling Jacket	9.99	14.95	19.84	24.61	29.22

NOTE (1): The speeds presented above for the configurations tested used the same constant power required as that for each baseline velocity

Table 5
CONFIGURATION FRONTAL AREAS

TEST NUMBER	CONFIGURATION	FRONTAL AREA (FT^2)	Coefficient of Drag (C_d)
1	Racing Position (Baseline)	3.68	0.93
2	Touring Position	4.55	1.00
3	Aerobar	3.45	0.81
4	Back Wheel Disk Cover	3.66 (1)	0.88
5	Tri-spoke Front Wheel	3.67 (1)	0.90
6	Aero Fairing	- -	- -
7	Aero Combination (1,3,4,5)	- -	- -
8	Cycling Jacket	4.21	0.98

Note: (1) Frontal area is a rough approximation based upon the cumulative results from Coastdown and Level Constant RPM studies.

Table 6

COST VERSUS TIME SAVINGS FOR A CYCLIST AT 20 MPH

TEST #	CONFIGURATION	PRODUCT NAME	MANUFACTURER	RETAIL COST ($)	(1) TIME SAVINGS (SEC)	COST PER SECOND SAVED ($)
1	RACING POSTION (BASELINE)	- -	- -	- -	0	- -
2	TOURING POSITION	- -	- -	- -	-60.50	- -
3	CLIP-ON AEROBAR	PROFILE CLIP-ONS	PROFILE	65	106.59	0.61
4	BACK WHEEL DISK COVER	UNI TITANIUM	UNI-USA	64.95	35.82	1.81
5	TRI-SPOKE WHEEL	ZIPP 3000	ZIPP	885	26.49	33.41
6	AERO FAIRING	BREEZE CHEATER	FAIRFIELD ENGINEERING	250	65.80	3.80
7	AERO COMBINATION (1,3,4,5)	(1,3,4,5)	(1,3,4,5)	1014.95	127.72	7.95
8	CYCLING JACKET	CYCLING JACKET	BURLEY	85	-36.75	-2.31

NOTE (1): Time savings as compared to cyclists in the racing position during a 25 miles ride, on a relatively flat course.

Table 7

COST VERSUS TIME SAVINGS FOR A CYCLIST AT 25 MPH

TEST #	CONFIGURATION	PRODUCT NAME	MANUFACTURER	RETAIL COST ($)	(1) TIME SAVINGS (SEC)	COST PER SECOND SAVED ($)
1	RACING POSTION (BASELINE)	- -	- -	- -	0	- -
2	TOURING POSITION	- -	- -	- -	-92.74	- -
3	CLIP-ON AEROBAR	PROFILE CLIP-ONS	PROFILE	65	148.74	0.44
4	BACK WHEEL DISK COVER	UNI TITANIUM	UNI-USA	64.95	46.97	1.38
5	TRI-SPOKE WHEEL	ZIPP 3000	ZIPP	885	30.95	28.59
6	AERO FAIRING	BREEZE CHEATER	FAIRFIELD ENGINEERING	250	85.45	2.93
7	AERO COMBINATION (1,3,4,5)	(1,3,4,5)	(1,3,4,5)	1014.95	165.83	6.12
8	CYCLING JACKET	CYCLING JACKET	BURLEY	85	-56.31	-1.51

NOTE (1): Time savings as compared to cyclists in the racing position during a 25 miles ride, on a relatively flat course.

Table 8

COST VERSUS TIME SAVINGS FOR A CYCLIST AT 30 MPH

TEST #	CONFIGURATION	PRODUCT NAME	MANUFACTURER	RETAIL COST ($)	(1) TIME SAVINGS (SEC)	COST PER SECOND SAVED ($)
1	RACING POSTION (BASELINE)	- -	- -	- -	0	- -
2	TOURING POSITION	- -	- -	- -	-132.64	- -
3	CLIP-ON AEROBAR	PROFILE CLIP-ONS	PROFILE	65	197.08	0.33
4	BACK WHEEL DISK COVER	UNI TITANIUM	UNI-USA	64.95	59.04	1.10
5	TRI-SPOKE WHEEL	ZIPP 3000	ZIPP	885	34.55	25.62
6	AERO FAIRING	BREEZE CHEATER	FAIRFIELD ENGINEERING	250	106.39	2.35
7	AERO COMBINATION (1,3,4,5)	(1,3,4,5)	(1,3,4,5)	1014.95	206.37	4.92
8	CYCLING JACKET	CYCLING JACKET	BURLEY	85	-80.02	-1.06

NOTE (1): Time savings as compared to cyclists in the racing position during a 25 miles ride, on a relatively flat course.

Figure 1
Photograph of Clip-on Aero Bar Configuration

Figure 2
Photograph of Back Wheel Disk Cover Configuration

Figure 3
Photograph of Tri-Spoke Front Wheel Configuration

Figure 4
Photograph of Aero Fairing Configuration

Figure 5
Photograph of Cyclist in the Cycling Jacket Configuration

Figure 6

Photograph of Cyclist in the Racing (Baseline) Position

Figure 7
Photograph of Cyclist in the Touring Position

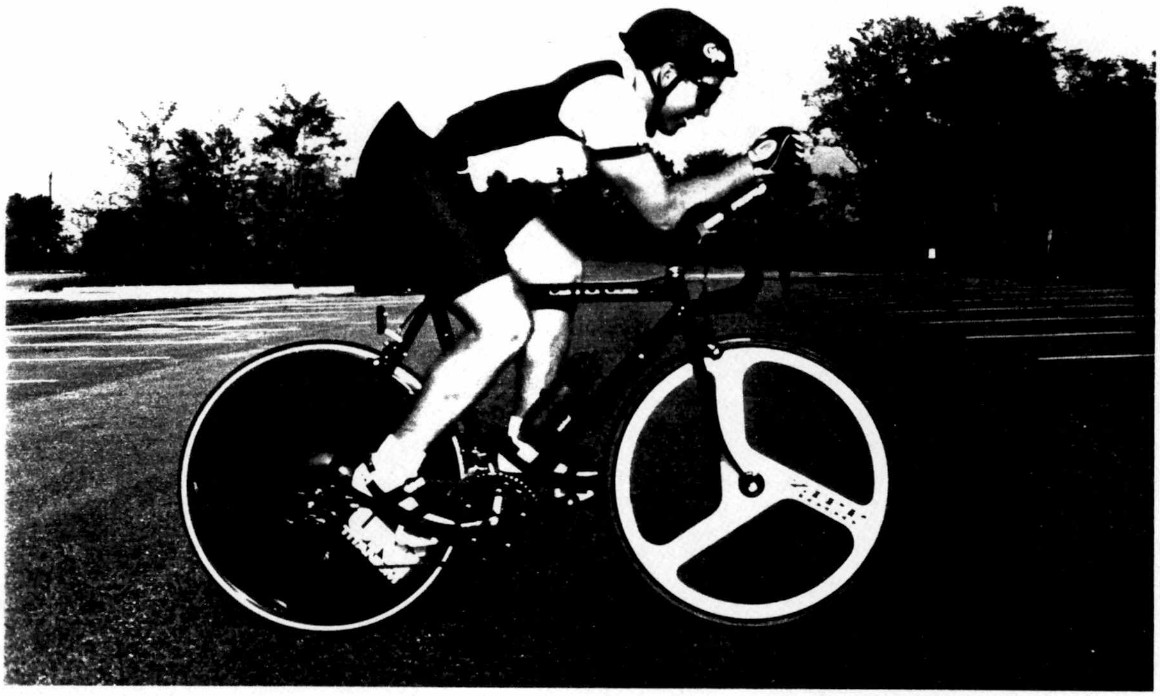

Figure 8
Photograph of Aero Combination Configuration

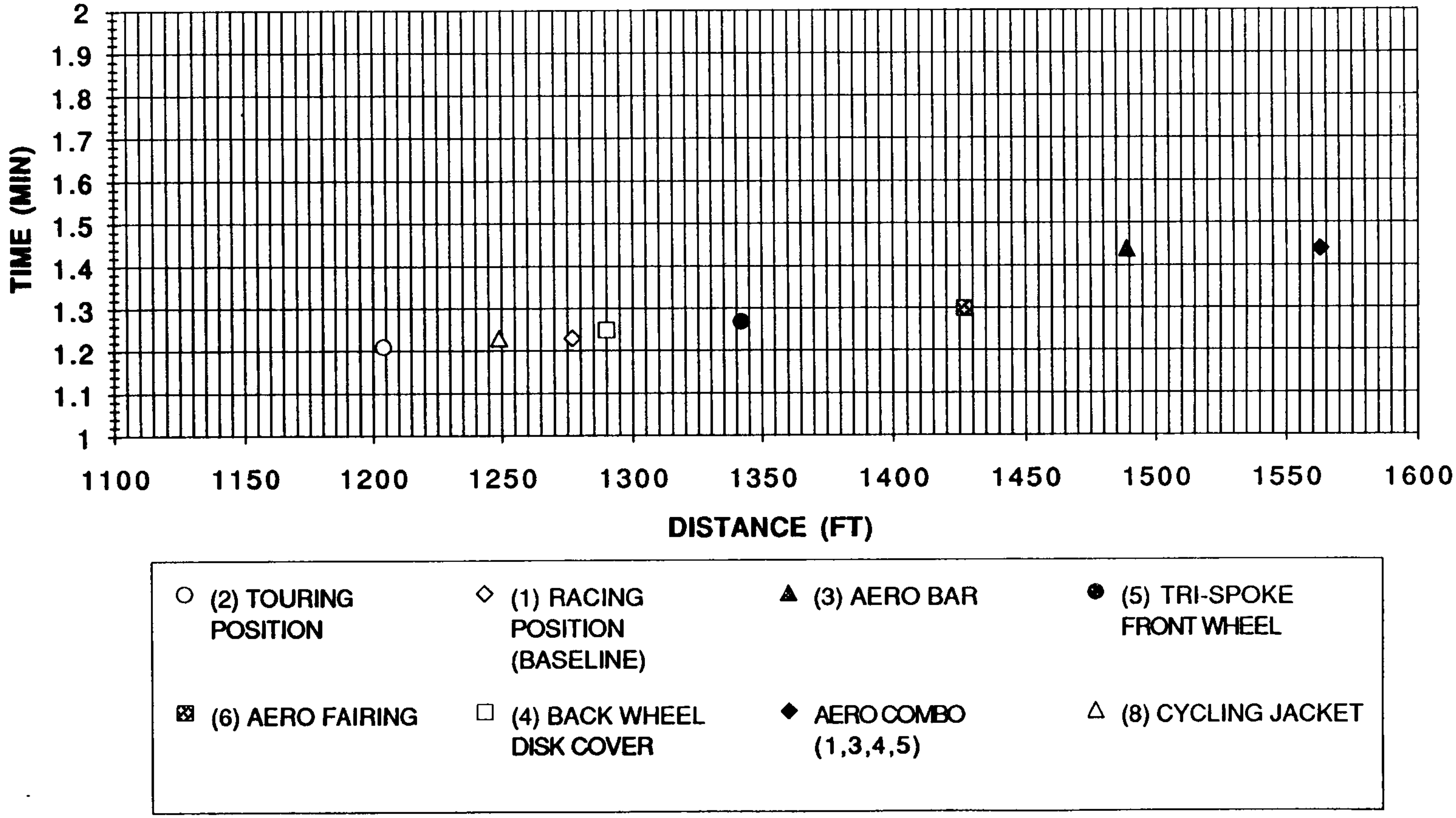

Figure 9
Coastdown Distance Traveled Versus Time

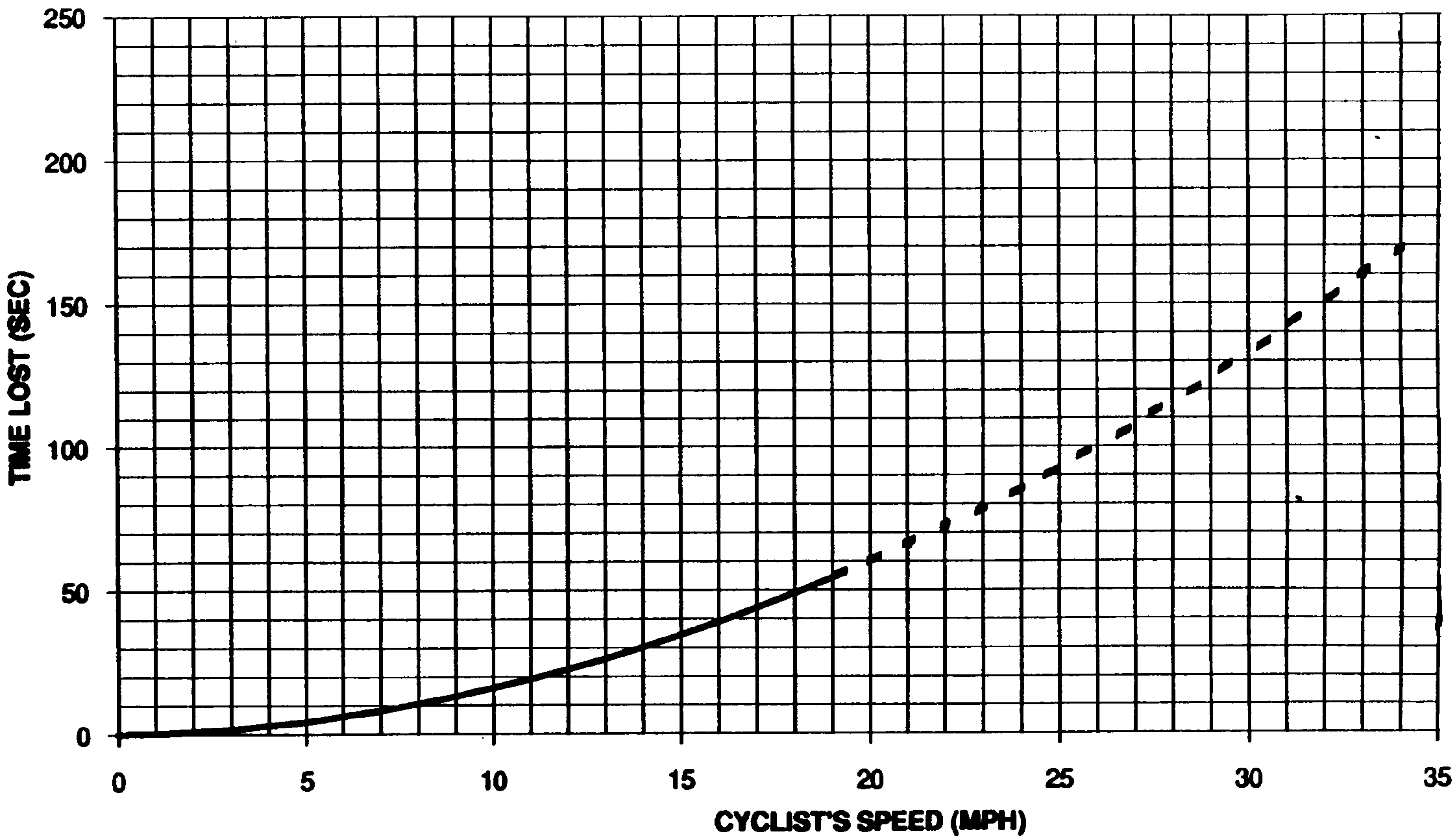

Figure 10
Time Lost Using Touring Position on a 25 Mile Course

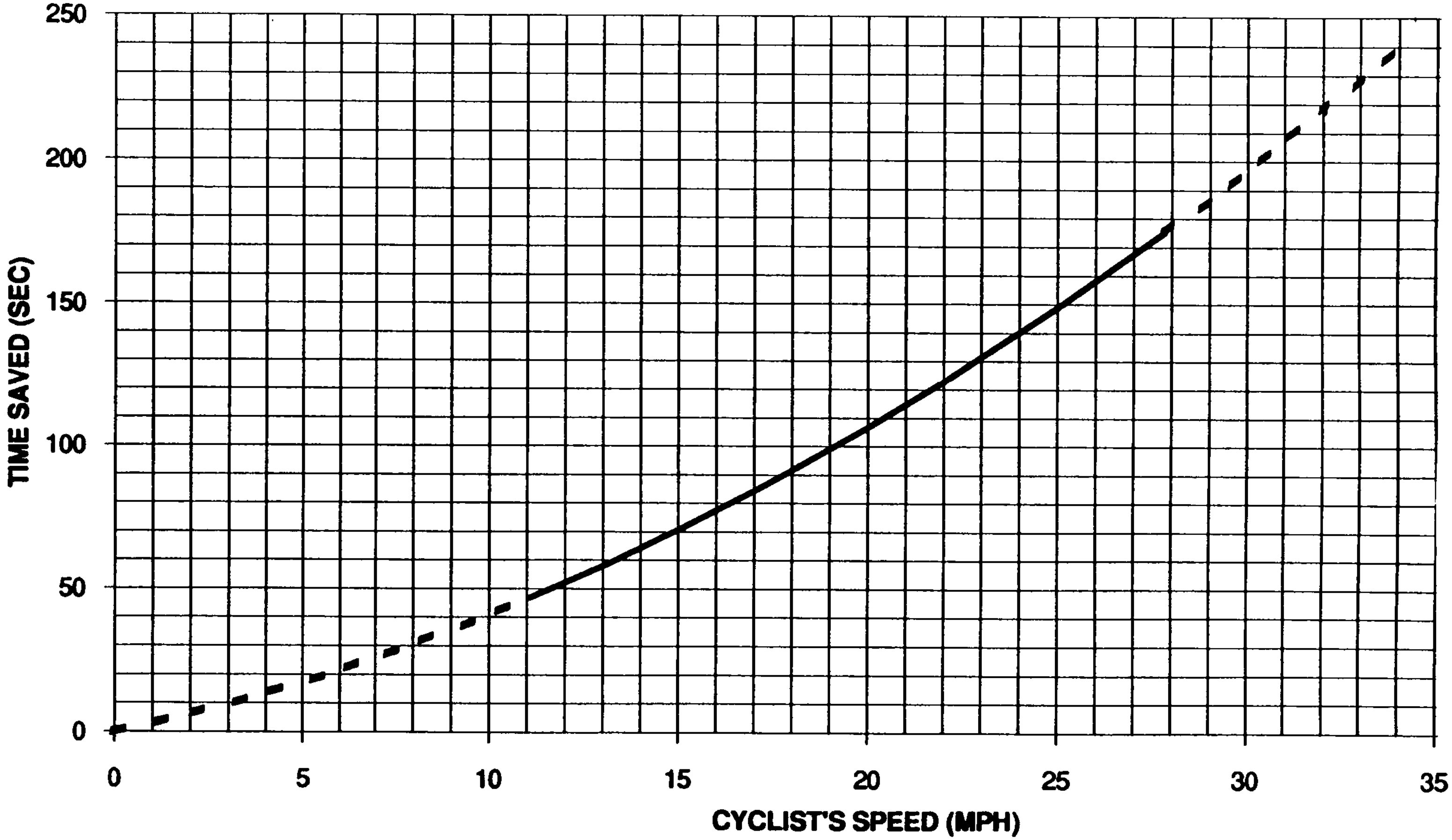

Figure 11

Time Saved Using Aerobars on a 25 Mile Course

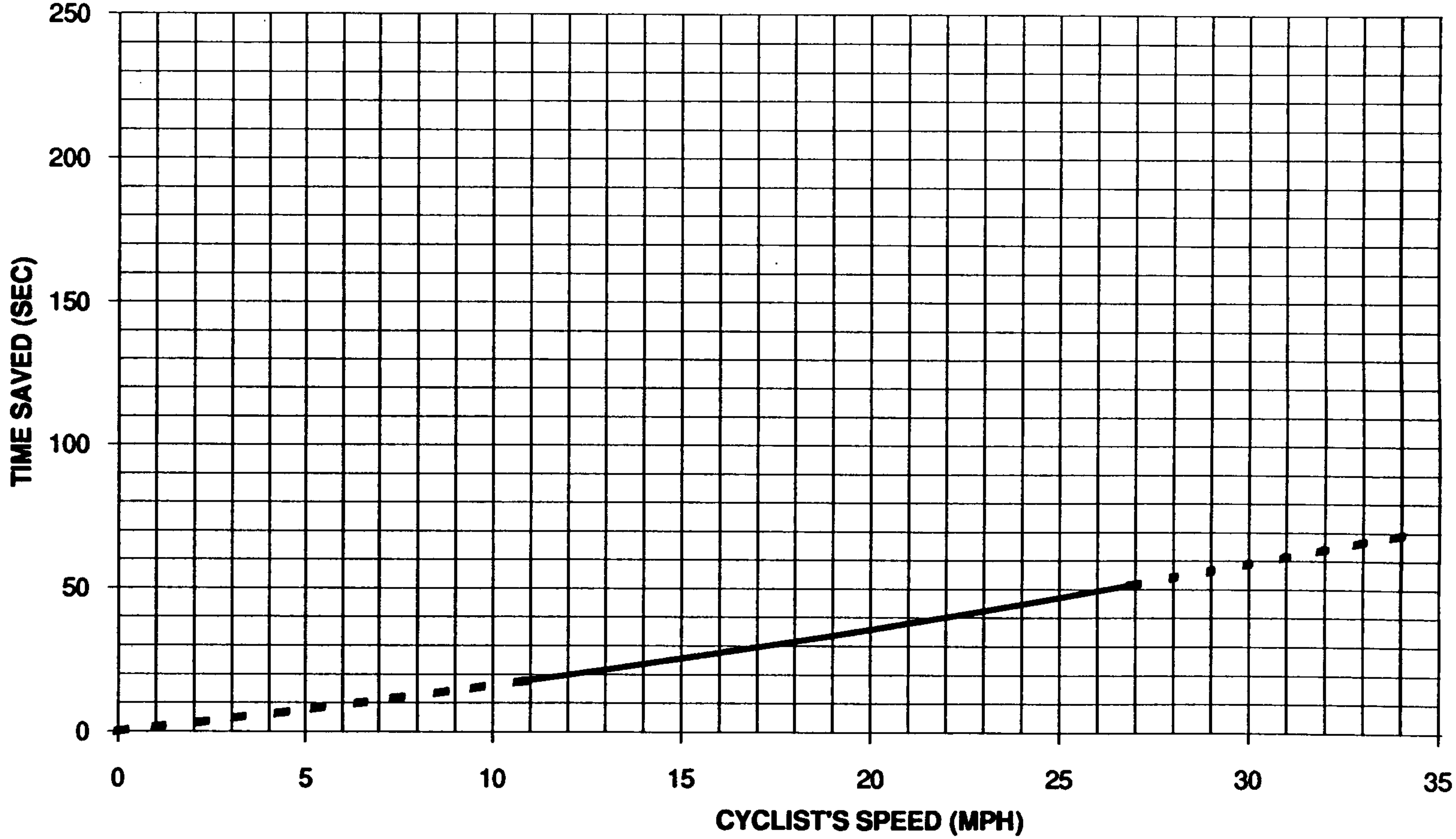

Figure 12

Time Saved Using Back Wheel Disk Cover on a 25 Mile Course

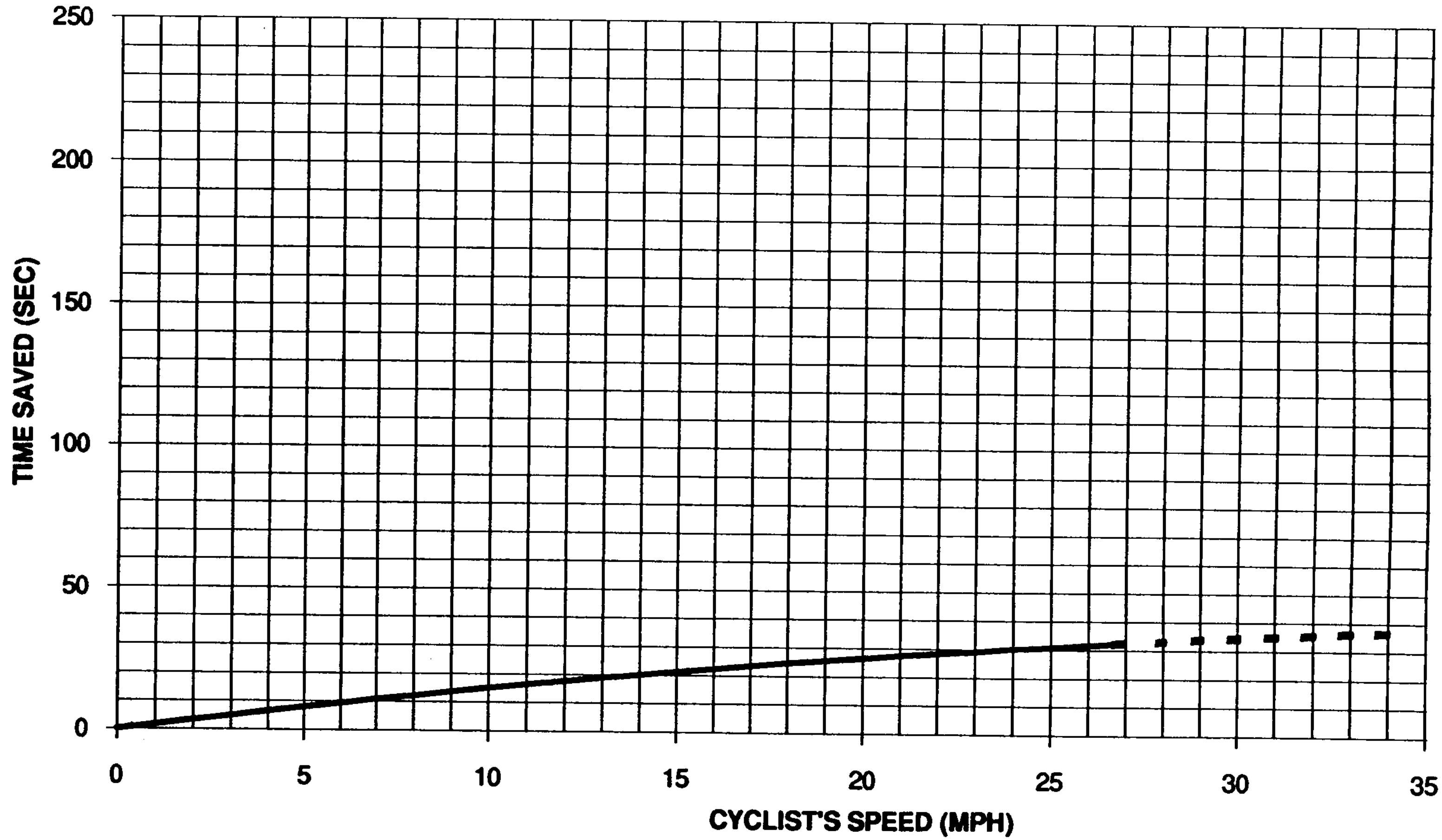

Figure 13

Time Saved Using Tri-Spoke Front Wheel on a 25 Mile Course

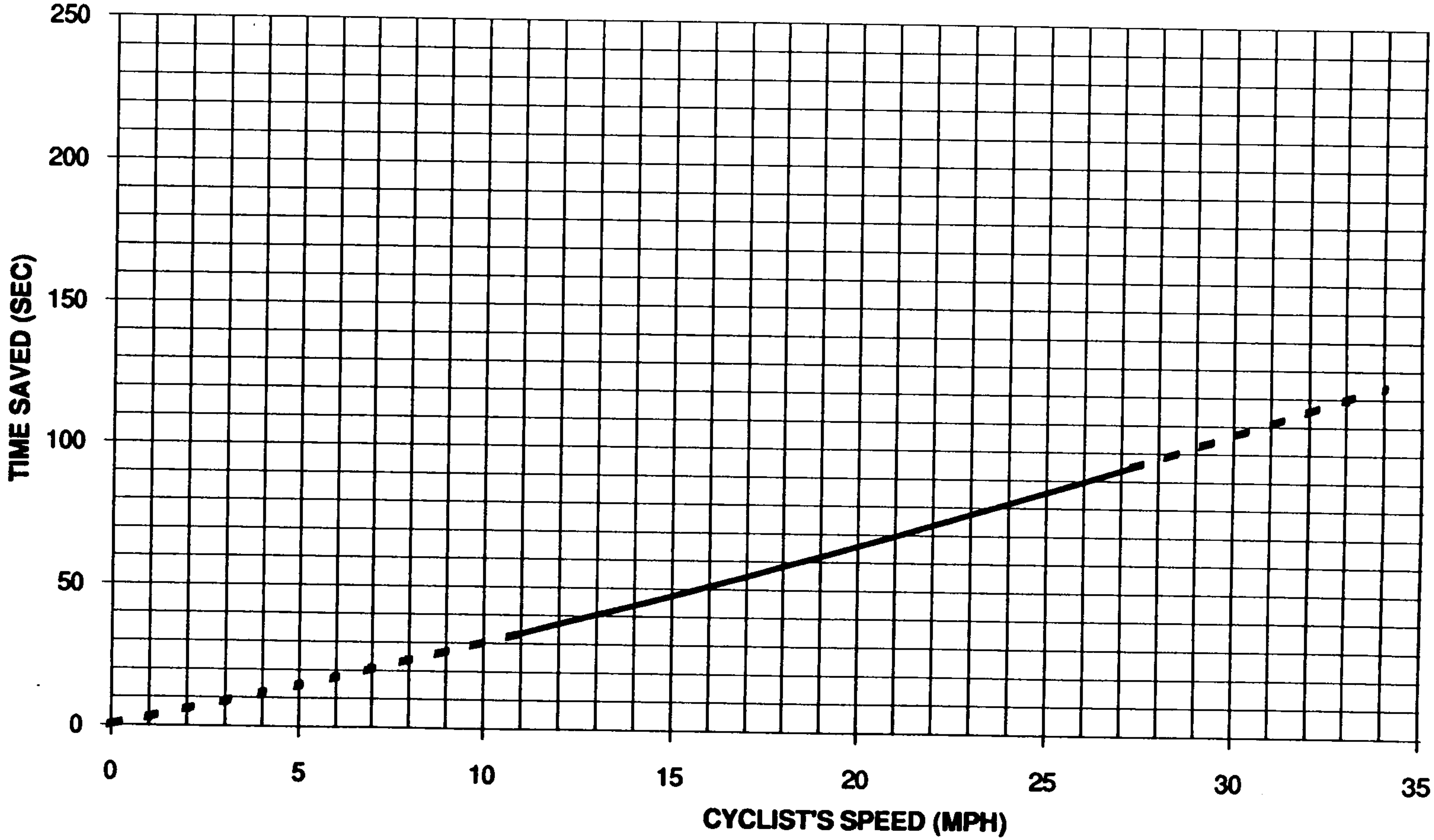

Figure 14

Time Saved Using Aero Fairing on a 25 Mile Course

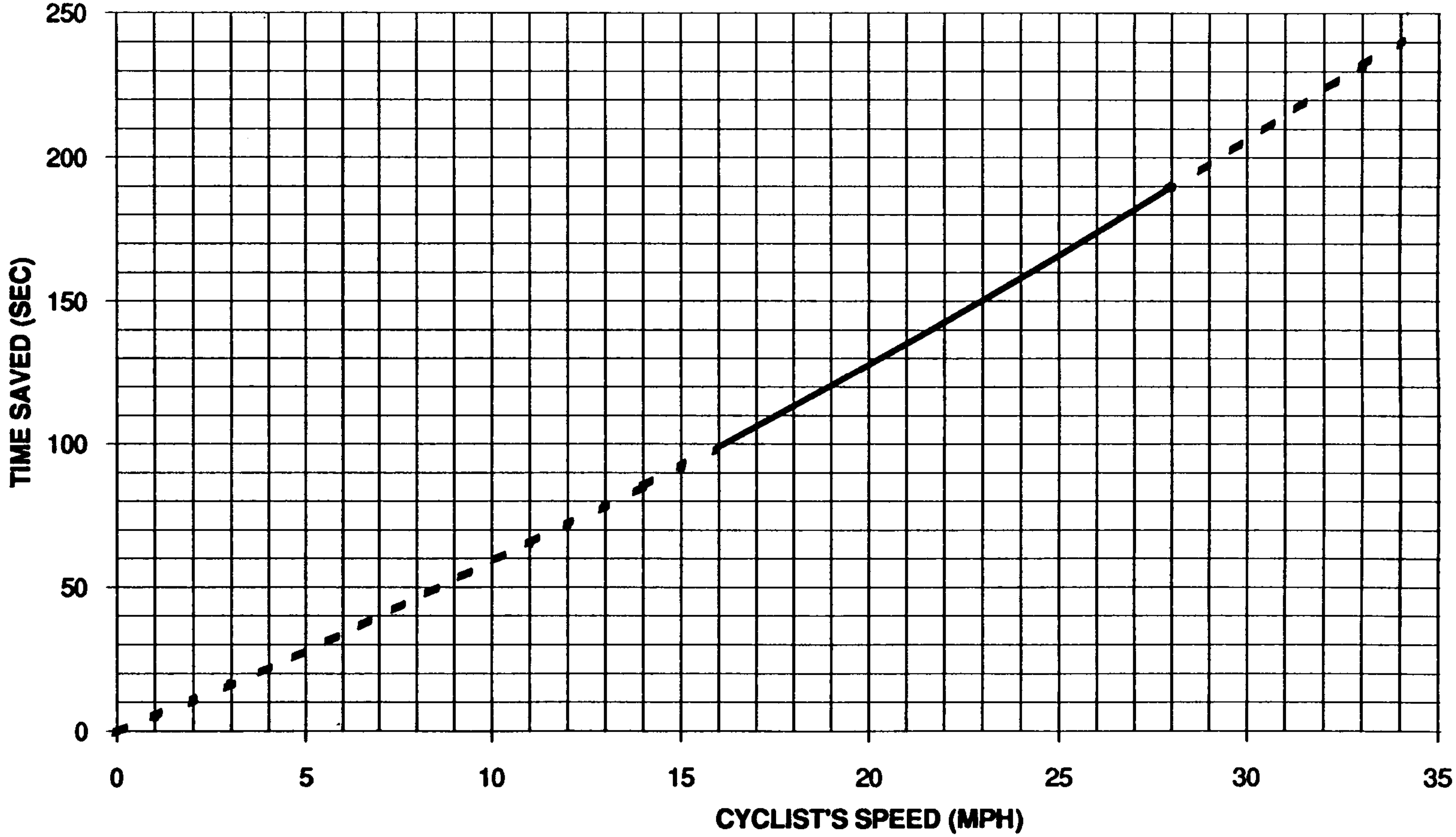

Figure 15

Time Saved Using Aero Combination (1,3,4,5) on a 25 Mile Course

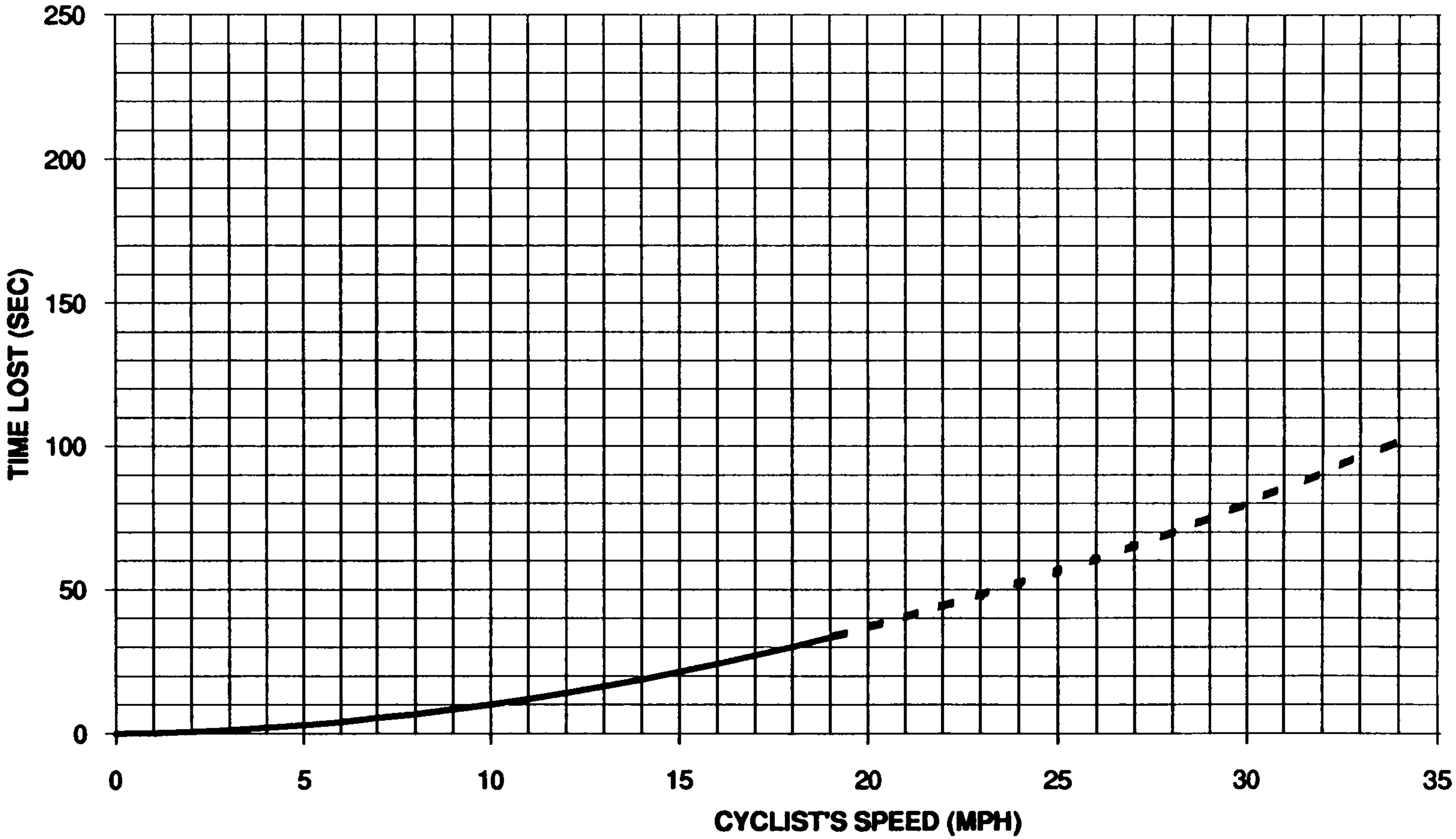

Figure 16

Time Lost Using Cycling Jacket on a 25 Mile Course

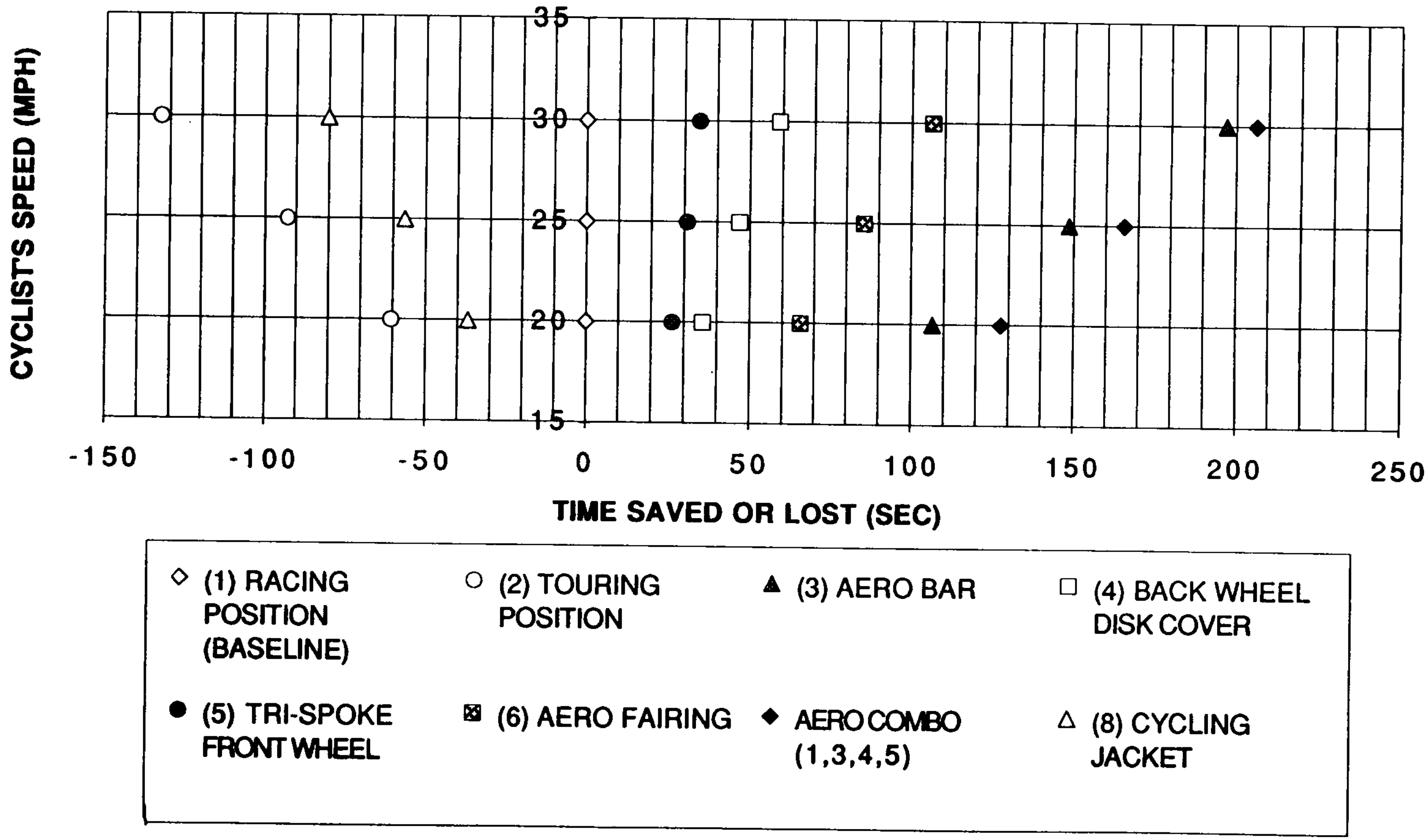

Figure 17

Time Saved or Lost for a Cyclist Traveling at 20, 25, and 30 MPH

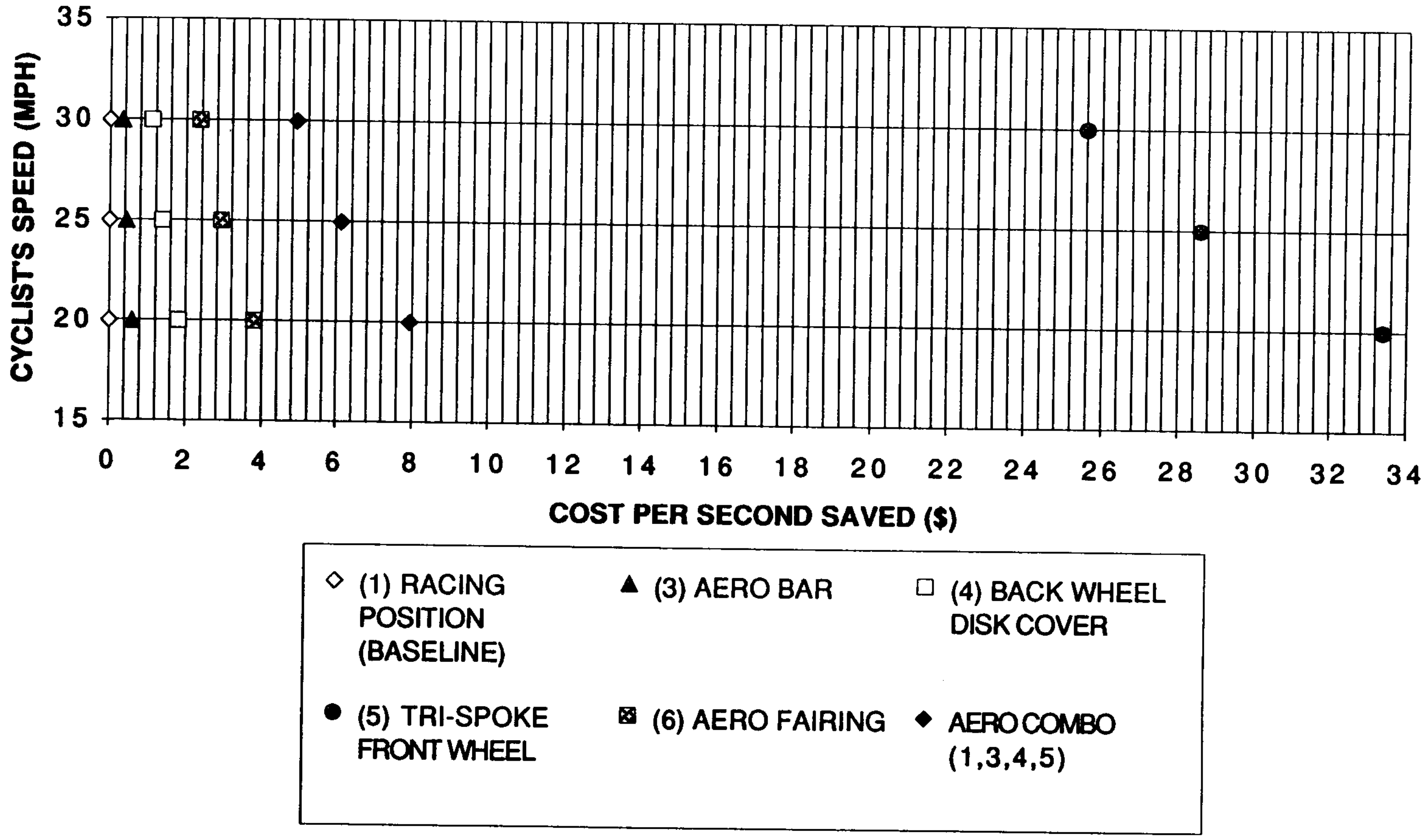

Figure 18
Cost Per Second for a Cyclist Traveling at 20, 25, and 30 MPH

VITA

Michael Joseph Meyers was born in Syracuse, New York on July 26, 1962. He attended elementary schools in both North Syracuse and Columbus Ohio. He graduated from Westerville North High School, Westerville, Ohio in 1980. The following September he entered University of Cincinnati College of Engineering Co-operative Education Program where he worked for Control Data Corporation as a Structural Analyst during his education. In June of 1985 he received a Bachelor of Science in Aerospace Engineering.

He then accepted a position as a flight test engineer at the Rotary Wing Aircraft Test Directorate, Naval Air Test Center, Patuxent River, Maryland. In March of 1988 he entered the University of Tennessee Space Institute, Patuxent River, Maryland program. In July 1989 he entered the United States Naval Test Pilot School and graduated in June 1990. He received a Master of Science in Aviation Systems from UTSI in May 1992.