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VALIDATION OF A SEGMENTED MODEL OF CRITICAL SPEED AND ITS DOMINANT PHYSIOLOGICAL COMPONENTS

by

Perry Jacobson

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Abstract

This study examined estimates of linear (distance vs. time; speed vs. 1/time; 3-segmented speed vs. 1/time) and nonlinear (2-parameter non linear; 3-parameter nonlinear (3PNL)) critical speed (CS) models for predicting 40 km time trial (TT) performance. Twenty one male cyclists ($\dot{V}O_2$ max 57.7 ± 6.1 $ml \cdot kg^{-1} \cdot min^{-1}$) performed 7 randomly assigned exhaustive time trials and a 40 km time trial (TT) on Kreitler Rollers. The time trials were of fixed distances eliciting finish times of 33.3 ±3.2 s, 75.5 ± 5.9 s, 2.1 ± 0.1 min, 3.7 ± 0.2 min, 7.0± 0.5 min, 16.6 ±1.0 min, and 34.6 ± 3.6 min. Linear CS estimates for the 3-segmented model were determined from 3 points between 0.5 and 2.5 min (CS-short); 3 points between 2.5 and 15 min (CS-medium) and 2 points 15 and 30 min (CS-long). The other models were calculated using all 7 points. Multiple regression analysis was used to determine which physiological variables made the most significant contribution to performance in each domain of the 3-segmented model. The mean speed of the 40 km time trial (33.3 $km \cdot h^{-1}$) was significantly faster than MLSS speed (31.4 $km \cdot h^{-1}$). CS estimates from 3PNL (33.4 $km \cdot h^{-1}$) and CS-long (33.2 $km \cdot h^{-1}$) were the only models which were not significantly different from the 40 km TT. The physiological variables which were found to make a significant contribution to the 3 segmented models were: speed at $\dot{V}O_2$ max, peak power averaged over 1 second (short model); MLSS, speed at $\dot{V}O_2$ max (medium model); MLSS, $\dot{V}O_2^{2/3}$ max, FFVT (long model). These results do not support the theoretical concept that endurance performance can be estimated from CS modeling of short duration all-out tests of less than 15 min in duration, but demonstrate that the new 3-segmented long model may accurately predict 40 km TT performance together with the 3PNL model.

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List of Definitions

Term	Definition
Anaerobic Capacity	The total amount of energy that can be produced by the anaerobic energy system
Anaerobic Power	The maximal amount of energy that can be produced by the anaerobic energy system per unit time
Anaerobic Threshold	That intensity of workload or oxygen consumption in which anaerobic metabolism is accelerated
Anaerobic Work Capacity	A finite amount of work that can be performed above critical power, regardless of the rate at which the work is performed
Critical Power	The power output that can be sustained until the gradual accumulation of fatigue inducing factors limit maintenance of that power output
Individual Anaerobic Threshold	A mathematical model of lactate produced in exercising muscles which represents a metabolic rate where elimination of lactate from the muscles is maximal and equal to production
Maximal Lactate Steady State	The highest exercise intensity which can be sustained with a maximum increase of 1.0 $mmol \cdot L^{-1}$ in blood lactate levels in the last 20 minutes of constant workload exercise
Maximal Oxygen Consumption ($\dot{V}O_2$ max)	The maximal volume of oxygen which can be consumed by an individual over a given period of time
O_2 pulse	Maximal amount of usable oxygen which can be pumped by the heart per beat
OBLA	Onset of blood lactate accumulation at an exercise intensity where the blood lactate concentration is equal to 4 $mmol \cdot L^{-1}$
Ventilatory Threshold	A measurement of the anaerobic threshold detected by the measurement of expired ventilatory gases including V_E, $\dot{V}O_2$ and $\dot{V}CO_2$

CHAPTER 1: INTRODUCTION

The relationship between power and exercise time to exhaustion was first introduced by Monod and Scherrer (1965) in relation to isolated muscle groups. The power time relationship was hyperbolic in nature and its asymptote was defined as the power output which could be maintained without fatigue. The power output at the asymptote has been termed critical power (CP) and studies have expanded the CP model to include working groups of muscles in cycling (Moritani et al., 1981), running (Hughson et al., 1984) and various other sports such as kayaking (Ginn & Mackinnon, 1989) and swimming (Wakayoshi et al., 1992). Using field tests, actual performance may be measured with the term critical speed (CS) replacing the power term.

The CP function can be determined by performing a series of timed exercise trials to fatigue or by timed maximal efforts at set distances. Housh et al. (1990) recommended that 3-5 trials be used to produce this function with a minimum time difference of 5 minutes between the shortest and longest trials. From these non-invasive tests, an intensity can be predicted which should be sustainable for a long time (Monod & Scherrer, 1965). This could provide valuable information to athletes for the purposes of training and predicting performance.

It is now apparent that CP cannot be maintained without fatigue which may be explained by factors such as lactic acid accumulation, creatine phosphate depletion, and other fatigue inducing factors (Housh et al., 1989). CP is significantly higher than the power associated with the lactate threshold (Housh et al., 1989), the ventilatory threshold (Kranenburg & Smith, 1996) and the individual anaerobic threshold (McLellan &

Cheung, 1992) and will therefore lead to fatigue. In tests at CP, exhaustion has been found to occur between 30 and 60 minutes (Hill, 1993) and as low as 16.43 ± 6.08 minutes in runners (Housh et al., 1992).

There are several methods that are currently used to determine CP (Figure 1). From the original hyperbolic relationship (figure 1d) CP is determined as the asymptote of the hyperbola. Monod and Scherrer (1965) transformed the hyperbolic relationship to a linear relationship between work and time and used this relationship to calculate CP as the slope of the regression line (figure 1a). Another model (figure 1b) currently used in laboratories uses the relationship between power and the inverse of time where CP is equivalent to the y-intercept (Whipp et al., 1992).

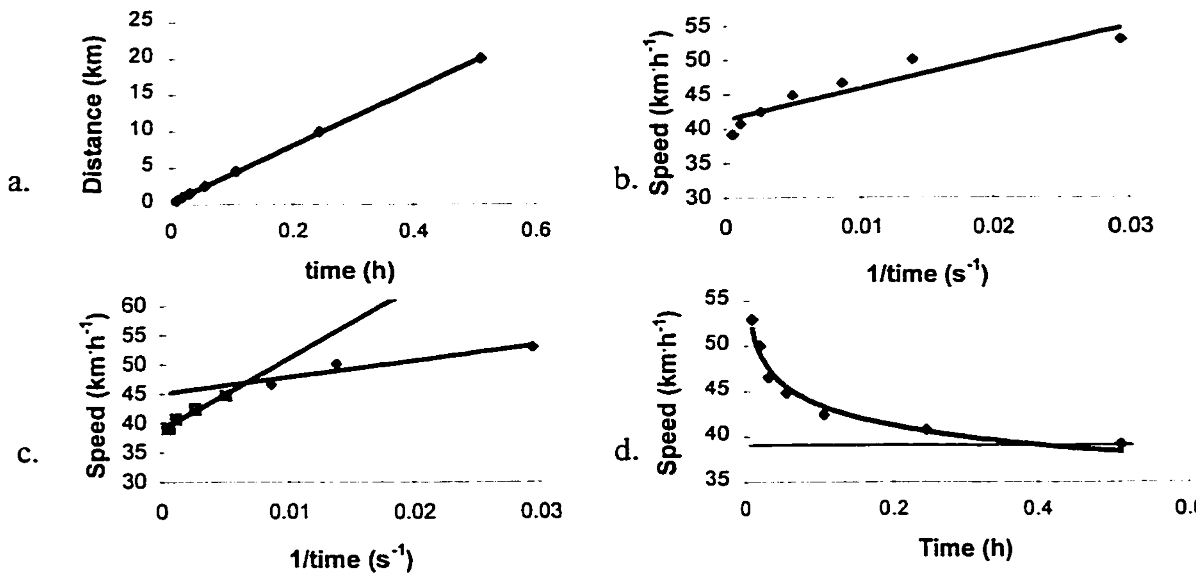


Figure 1. Four models of cycling performance using 7 timed distances to exhaustion a) distance vs. time where CS is equal to the slope; y=38.8x+0.28 b) speed vs. 1/time where CS is equal to the y-intercept; y=455.2x+41.24 c) two component segmented speed vs. 1/time model; y=1204.7x+38.97, y=280.56x+45.0 d)speed vs. time with hyperbolic curve where CS is equal to the asymptote.

Gaesser et al. (1995) addressed some of the limitations associated with CP models when they compared parameter estimates derived from two linear models, a two parameter nonlinear model, a three parameter nonlinear (3PNL) model and an exponential model (Table 1).

Table 1. The five models of critical power (Gaesser et al., 1995).

Model	Equation	Variables
Hyperbolic	$t=W'/(P-P_c)$	W'=anaerobic work capacity P =power P_c=critical power t=time to exhaustion
linear: work-time	$P\cdot t=W'+(P_c t)$	same as above
linear: power-inverse time	$P=(W'/t)+P_c$	same as above
three parameter non-linear	$t=(W'/(P-P_c)) - (W'/(P_{max}-P_c))$	P_{max}=maximal instantaneous power
exponential	$P=P_c+(P_{max}-P_c)\exp(-t/\tau)$	τ=time constant

All five models were found to fit the data very closely ($0.96<r^2<0.99$) however, each produced different estimates of CP (195W-242W). The three parameter non-linear model was found to be the best determinant of critical power because it removed the major limitations of the traditional hyperbolic model which were suggested to be : 1) the assumption of infinite power as time approaches zero and 2) that the anaerobic work capacity (AWC) is exhausted at the time of fatigue. Gaesser et al. (1995) suggested that this model was more statistically sound than the linear models and that it was not significantly different from the ventilatory threshold (Ventilatory threshold = 189 ± 34W, 3PNL = 197 ± 30 W).

It is suggested that the determination of CP should be valid from both linear and nonlinear models as long as each performance test is a true maximal effort (Hill, 1993), and that CP tests should last between 1 and 10 minutes (Poole et al. 1986) with at least five minutes separating the longest and shortest trials (Housh et al. 1990). Furthermore, for a test to be valid based on the hyperbolic model or one of its derivations, the duration of the tests should be within the range of time in which the model is truly hyperbolic which is suggested to be in the time frame of between 1 and 40 minutes (Hill, 1993).

In CP tests of short duration (less than three minutes) an exponential model was found to fit the data better than any of the other models (Hopkins et al., 1989). This suggests that CP may have more than one component and that tests using different time frames may each be fit by separate models.

A limitation should exist in the CP model which prevents subjects from performing without exhaustion. In order to perform without exhaustion, many physiological systems must combine to produce the required amount of energy while limiting fatigue inducing factors. Physiological variables which have been identified as contributing to long and short term exercise range from maximal oxygen uptake ($\dot{V}O_2$ max) (Davies & Thompson, 1979) to anaerobic capacity (Nebelsick-Gullett et al., 1988). The CP function is composed of both aerobic and anaerobic components and therefore, factors from each system should be included to produce long term exercise without exhaustion. Katz and Katz, (1994) found that the energy contribution of the aerobic and anaerobic systems intersected at 140.2 seconds. This may be related to CP such that there may be separate CP estimates determined by the dominant time phase of each energy system.

Based on two homogeneous groups of endurance and anaerobic athletes, Nelson et al. (1997) found that the power-inverse time model fit the data better if it was segmented into two linear models - one for short duration tests (<2.5 min) and one for long tests (figure 1d). Using this segmented model, CP values for the short duration tests were found to be significantly different than CP values from the longer tests ($p<0.05$). Both the long and short duration CP values were significantly different that CP calculated using all trials. Nelson et al. (1997) concluded that using the power-inverse time model, trials of less than 2.5 minutes have a significant effect on the calculation of CP base upon a single component model.

This study also found that the relationship between power and time to exhaustion may be fit by a model using a power curve of the form $y=bx^m$ (Figure 2). In this form, b provided an indication of the athletes maximal (short duration) power capabilities and m described the degradation of the power curve which may be used as index of an athletes ability to sustain prolonged exercise intensities.

Another model which compares the relationship between speed and the log of distance (Bunc & Moravec, 1981), was also used to differentiate athlete performance using short, middle and long distance runners at distances between 400m and 42 km. From this model, the slope of the relationship was used to characterize the endurance capability of runners (Bunc et al., 1992), where a less negative slope indicated stronger endurance capabilities of the athlete (Figure 2).

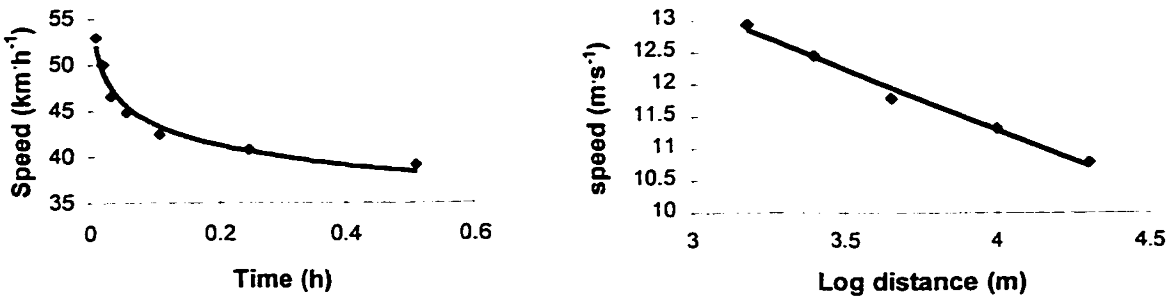


Figure 2. Models of performance used to differentiate athlete characteristics. a) The power curve model. b) The logarithmic model.

Studies have attempted to establish the validity of the CP model by having subjects exercise for as long as possible at the intensity equal to CP. Performance in these criterion tests however, rarely meet the expectations of the researchers. Validity research by Pepper et. al. (1992) and by McLellan and Cheung (1992) found that their subjects could not ride at CP for the expected duration of one hour, finishing at 16.43 ± 6.08 minutes and 20.5 ± 4.5 minutes respectively. This suggests that the concept of CP is more complex in the real world than the model predicts. The theory of CP suggests that the model can predict a power output that would be sustainable for a very long time without fatigue. In practical use however, results have shown that CP calculated using current models may only be sustainable for approximately 40 minutes. Thus, there is a disparity between the concept of CP and its actual use in exercise physiology laboratories.

Although, Hill (1993) states that the estimation of CP is valid as long as the tests are performed within the time frame in which the model is truly hyperbolic (1-40 minutes), there is no evidence to suggest that the CP model cannot be expanded to include shorter and longer events with a different model. Thus, new models may exist which incorporate times outside the time frame in which the traditional CP model is truly hyperbolic in nature.

Statement of the Problem

CP Models: Although several models are currently available for the determination of CP each model produces a different estimate of CP (Gaesser et al. 1995). With the development of a new model (Nelson et al., 1997), a study was required to investigate the physiological validity of this segmented model and the other models. Current estimations of CP or CS do not meet the standard of determining an intensity which can be sustained for 40-60 minutes without fatigue. Thus, there is a lack of criteria for the use of each model under specific conditions.

Physiological Components of CP: The basic physiological components of the CP model have not been researched beyond its relationship to the anaerobic threshold (McLellan & Cheung, 1992). A better understanding of the CP concept may be achieved by examining a broad spectrum of physiological variables with CP models.

Purpose

The purpose of this investigation was to determine if CS models could be explained by specific physiological variables. The models included: 1) distance vs. time

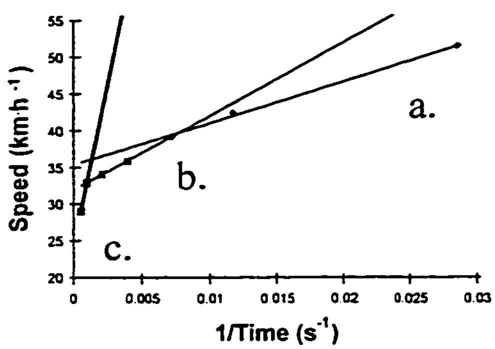
2) speed vs. inverse time 3) segmented speed vs. inverse time 4) hyperbolic 5) three parameter nonlinear. The CS derived from each model was also compared to the speed of a 40 km criterion trial which would validate the CS estimate from the best model based upon a real world test.

In addition, the new segmented model using the speed-inverse time relationship was intended to expand the time frame in which the overall model is valid. Using up to three time segments, the new CS model may allow for accurate prediction of performance times up to one hour. The validation of this model may also allow the CS concept to be presented in distinctive physiological domains. Each section of the 3-segment model was examined to determine which physiological variable most significantly contributed to that section of the model. The physiological parameters were: $\dot{V}O_2$ max, minimum speed at $\dot{V}O_2$ max, oxygen pulse, maximal lactate steady state, maximal instantaneous power, fat free thigh mass, %body fat, and muscle fiber type.

The power curve and speed vs. log distance models examined the preferred race distance or performance domain of each subject.

Hypothesis

It was hypothesized that the CS model which would have the best fit and explanation of physiological performance would be the three component speed-inverse time model within the time frame of 30 second to 40 minutes. The first linear section of the model would be from 30 seconds to approximately 2.5 minutes; the second linear section of the model would last from approximately 2.5 minutes to 15 minutes; and a third linear component would extend from 15 minutes up to 40 minutes (Figure 3). The dominant physiological variables contributing to the short duration CS component would be anaerobic in nature with maximum instantaneous power, thigh muscle mass and fast twitch fiber percentage contributing to the performance. The middle time domain would be aerobic power in nature with absolute $\dot{V}O_2$ max and speed at $\dot{V}O_2$ max being the dominant variables. The final segment would be aerobic capacity and should be dominated by the slow twitch fiber percentage and maximal lactate steady state.



Predictor variable	Time frame
a. type II fiber, power	30s-2.5min
b. VO_2 max, vVO_2 max	2.5min-15min
c. MLSS, type I fiber	15min-40min

Figure 3. Hypothetical segmented model of speed vs. 1/time and the dominant physiological variables associated with each segment. Taken from a single subject case study (Jacobson, 1997).

It was also hypothesized that the logarithmic and power models would provide means of differentiating cyclists into sprint predominant or endurance predominant groups. Sprint predominant cyclists would produce a more negative b value from the logarithmic models, whereas using the power model sprint predominant athletes would demonstrate a high b value and low exponential values.

CHAPTER 2: LITERATURE REVIEW

The Critical Power Concept

The critical power (CP) function is defined by the relationship between power and time to exhaustion in a working muscle (Hill, 1993). This relationship is hyperbolic in nature and was initially defined by Monod and Scherrer (1965) to produce an estimation of a power output which could be sustained indefinitely without fatigue. The CP function can be produced by a series of simple timed exercise bouts to exhaustion without the complication of invasive procedures or complex equipment. Critical power has since been modified to incorporate the time to exhaustion of muscle groups working together to produce a full range of motion (Moritani et al., 1981). Because the test can be applied to several muscles working together, the critical power function can be used to determine the time to fatigue of any group of muscles which work together in a sport specific setting. Critical power has been researched extensively in cyclists (Moritani et al., 1981), runners (Hughson et al., 1984; Kranenburg & Smith, 1996) and various other specific sports including swimming (Wakayoshi et al., 1992) and kayaking (Ginn & Mackinnon, 1989). The ability of the CP function to be applied to many sports and the simplicity of the test has prompted many studies to determine the validity of the test and to develop a model which allows for the prediction of future performance times in athletes (Hill, 1993).

Monod and Scherrer (1965) initially suggested the hyperbolic relationship produced by 3-5 exhaustive bouts of exercise up to 30 minutes in individual isolated muscles. They then transformed the hyperbolic power-time relationship into a linear relationship between work and time to exhaustion. The linear relationship is defined by the equation $W_{lim}=a+b\cdot t_{lim}$, in which the slope b is CP and the y-intercept a, represents the anaerobic work capacity (AWC) (Moritani et al., 1981). Monod and Scherrer (1965) proposed that the CP determined from this test would produce a power intensity which could be maintained for a long period of time without fatigue. This statement suggests that a subject could exercise at intensities up to and including CP indefinitely without reaching exhaustion.

One other linear model is also widely used for the determination of CP. Whipp et al. (1982) plotted the relationship of power vs. the inverse of time to produce the equation $P=W'\cdot t^{-1}+CP$, where P represents power and W' represents the AWC. From this relationship CP is determined by the y-intercept and AWC is determined by the slope of the line. All three models of CP can be produced from the same data and should produce the same estimates of CP and AWC (Hill, 1993). This is only true however, as long as the nonlinear model is truly hyperbolic. This generally limits the model to the range of 1-40 minutes (Hill, 1993).

Determination of Critical Power

Number of Trials

The critical power function can be determined by subjects exercising to exhaustion at several different work intensities. To measure CP, theoretically only two data points are needed to produce a straight line (Hill, 1993). Housh et al. (1990) compared the estimation of CP derived by using 2, 3, or 4 trials to exhaustion using the linear work-time model. The study concluded that using only two trials, the results were not significantly different from using all four trials. By using more than two data points, however, the line may be interpreted for its goodness of fit to the model. The r^2 value will therefore allow an interpretation of whether each exercise bout was indeed performed to exhaustion (Hill, 1993). Caution should be used when using a large number of trials as the demands on the subject increase and the time constraints for monitoring the athlete become too large (Hill, 1993).

Time Frame of Trials

The determination of CP has traditionally used time trials of 2-10 minutes. Poole et al. (1986) recommended that CP values were valid using trials lasting between 1 and 10 minutes. Other research has shown that the times of each trial should differ by at least 5 minutes (Housh et al., 1990). Few studies have been performed with trials lasting longer than 30 minutes. Hill (1993) suggested that the time of each trial is immaterial as long as they are within the time domain of the hyperbolic relationship. He also suggested that the recommendations of Housh et al. (1990) and Poole et al. (1986) were logical guidelines to follow. Other studies such as Wakayoshi et al. (1992) have used trials as short as 30 seconds to determine CS in swimming. Nelson et al (1997) suggest that trials lasting less than 2.5 minutes can significantly increase the CP values. Therefore, separate critical power analysis should be performed on all trials below 2.5 minutes and all trials above 2.5 minutes.

The CP function was found to be dependent upon the duration of the predictive exercise tests chosen. Bishop et al. (1998) produced the CP function using five trials lasting between 1-10 minutes. They calculated CP using three different combinations of three points for the CP regression analysis. CP was calculated using the three shortest trials, the three longest trials and the first, third and fifth trials. The results showed that there was a significant difference in CP values based upon the time frame of points chosen. Using shorter trials, higher values of CP were produced.

Rest Between Trials

Because the CP test is very demanding to the subject and requires repeated exercise bouts to exhaustion, studies have been performed to determine the amount of rest required between successive trials. Studies have provided between 30 minutes and 24 hours (Housh et al., 1990; Carnevale & Gaesser, 1991) of recovery time between all out exercise trials. Housh et al. (1990) performed 4 CP trials lasting between 1 and 10 minutes on 2 days separated by at least 24 hours. On each day, two trials were performed separated by 30 minutes. Critical power values using all 4 trials were not significantly different from CP values using all combinations of 2 and 3 trials. This suggests that no difference was found regardless of the rest period provided between testing trials. Bishop and Jenkins (1995) compared the results of CP estimates when subjects were given either 3 or 24 hours of rest between exercise trials. Using untrained women who were familiar with the protocol, parameter estimates did not significantly differ between groups.

Testing Cadence

In cycle ergometry, pedal cadence has also been studied as a confounding variable in the relationship between power and time to exhaustion. Hill et at. (1995) compared the estimation of CP when subjects pedaled at 60rpm, 100 rpm and a variable cadence chosen by the subject. The results demonstrated that CP estimates were significantly different ($p<0.001$) based upon the pedal cadence chosen. The estimation of CP was highest at 60 rpm and lowest at 100 rpm. The estimates for CP, using the non-linear power-time model, produced a difference of 6% between cadences of 60 and 100 rpm. These results may be explained by a difference in pedal efficiency at different cadences (Carnevale & Gaesser, 1991). The variable cadence model was the only model whose parameter estimates were independent of the regression model used.

Critical Power Models

Several of the models for the critical power function have been outlined previously in this review. All of the models are based upon the relationship between power and time to exhaustion in exercise. There are, however, several limitations to these models. The three models, that are based upon the original hyperbolic model, are only valid in the time frame in which the CP function is truly hyperbolic (Hill, 1993). There is a limit to the magnitude of power which can be sustained for even the shortest amount of time, and there is a time limit for the duration that the smallest power can be sustained. This imposes limits on the time frame in which the power time relationship is truly hyperbolic. Under these conditions the model is valid for the time frame between 1 and 40 minutes, with some individual subject variation (Hill, 1993). When the model was originally proposed by Monod and Scherrer (1965), CP was believed to be a power output which could be sustained for a very long time without fatigue. This statement may only be generalized to the time frame in which the model is valid (1-40 min). Within this time frame the CP model may be used as a measurement of aerobic and anaerobic fitness and as a tool to predict time to exhaustion for a given power output.

Gaesser et al. (1995) compared the CP parameter estimates determined by five different models of the data: two linear models (work-time, and power-inverse time), a two parameter hyperbolic model, a three-parameter nonlinear model and an exponential model. Each subject exercised at five power outputs to exhaustion ranging from 1-20 minutes in duration. The five models were analyzed for goodness of fit to the data using r^2 and the CP estimate was compared to the ventilatory threshold. The results of the regression analysis indicated that each of the models produced significantly different estimates.

The exponential model produced the highest estimation of CP, whereas the nonlinear models produced the lowest CP values with the three-parameter nonlinear model being the lowest (Table 2). The CP estimates from the five models were all highly correlated with each other ($0.78<r<0.99$). All of the models fit the data very well with high values of r^2 (Table 1). However, the linear power-inverse time model ($r^2=0.96$) had the lowest r^2 value.

Table 2. Critical power estimates and r^2 values of five different models (Gaesser et al., 1995)

Model	CP (W)	R^2
Three-parameter nonlinear	195	0.99
Two-parameter nonlinear	215	0.99
Linear (work-time)	224	0.99
Linear (Power-inverse time)	237	0.96
Exponential	242	1.00

One major difference found between the models was the relationship between CP and the ventilatory threshold for long term exercise. The ventilatory threshold was found at a mean of 189 ± 34 W which was significantly different from the CP estimate of every model, except the three-parameter nonlinear model. This finding contradicts previous research which has found that CP was significantly greater than the anaerobic threshold (McLellan & Cheung, 1992). Gaesser et al. (1995) concluded that although the two linear models and the two-parameter nonlinear models were mathematically equivalent, they do not produce equivalent parameter estimates for critical power. They also suggested that the nonlinear data should be treated with nonlinear analysis, with careful designation of the independent and dependent variables. The best model under these conditions was the three-parameter nonlinear model. Morton (1996) also found that using the three-parameter nonlinear model reduced the overestimation of CP produced by the other models.

A study comparing the two linear models to the two-parameter nonlinear model found that there was no difference in the parameter estimates derived from these three models (Smith & Hill, 1992). Similar results were found by Hill et al. (1995) in their investigation of the effect of pedal cadences and regression model on CP estimation. Hill et al. (1995) concluded that when variable cadence methodology was used there were no significant differences amongst the parameter estimates from the three models. Thus, it is important to consider pedal cadence methodology when comparing parameter estimates between studies which use different regression models (Hill et al., 1995).

Nelson et al. (1997) fit data of six CP tests between 30 seconds and 12 minutes to a power curve in the form $y=bx^m$. In this form the base b indicated the maximum power ability of the athletes and the exponent m indicated the degradation of the curve which defined the aerobic endurance ability of each subject. This model was found to fit the nonlinear data better than any other model. When subjects were grouped as sprint or endurance athletes, significant differences were found between values of both b and m between groups ($p<0.05$). This model may therefore, provide a classification of athletes based upon the characteristics of their individual power curve.

Another model has been proposed in the form $y=a+bz$. This model can distinguish between groups of endurance runners and is based on the relationship of running speed and distance covered on a semi-logarithmic scale. The slope b is used to separate runners into middle distance, long distance and marathon runners (Bunc et al. 1991) where the larger the dependence of the athlete on the anaerobic energy systems, the larger the value of b will be in the negative direction.

The same models may also be applied to activities in which speed is measured rather than power. Critical speed (CS) has been defined by the relationship between speed and time to exhaustion and follows the same principles as the CP model. Critical speed is more practical for use in field tests or in sports for which speed provides a more practical measure of performance than power (Kranenburg & Smith, 1996).

Critical Power as a Tool for Performance Prediction & Monitoring

Previous research studies on CP have used many combinations of regression models and testing methodology. Regardless of the technique used to derive the CP value, researchers have used the information both as a tool for monitoring training and as a means of predicting future performance times. The CP function incorporates the work of both the aerobic and anaerobic energy systems (Hill, 1993) and is, therefore, a useful training marker for many different types of athletes.

Gaesser and Wilson (1988) compared the effects of continuous and discontinuous training on the estimation of CP and AWC derived from the power-inverse time linear model. After six weeks of training both groups (n=11) increased in CP by 15% and 13% respectively. In these same subjects, there was no difference in mean AWC estimation after the six week training period.

CP was also found to increase in nine subjects after eight weeks of training at an intensity corresponding to CP (Jenkins & Quigley, 1992). The training group (n=12) had significantly increased their CP by a mean of 59.0 Watts (W) while the control group (n=6) showed a mean increase of 11.0 W. After the training period, there was no significant increase in the AWC component of the model. A second study by Jenkins and

Quigley (1992) compared the effect of high-intensity training on the CP parameters. Subjects (n=8) trained for eight weeks at an intensity which required five all out efforts for one minute separated by a five minute recovery period. AWC increased in these subjects by 49% (p<0.001) while their was no change in CP. These studies suggest that CP and AWC are both sensitive to training and each parameter will only respond to training which targets its underlying energy system.

The CP model may also be used to predict athlete performance times. Many studies have tested the CP parameters and used the model to extrapolate an estimation for a future performance (Table 3). Housh et al. (1989) compared the predicted time to exhaustion from the work-time model to the actual time to exhaustion at CP-20%, CP, CP+20%, CP+40%, and CP+60%. At CP-20%, 13 out of 14 subjects were able to cycle

Table 3. Comparison of the predicting ability of the critical power estimate from resent research studies.

Reference	Year	Model	CP or CS	Results of performance test at CP or CS
Hughson et al.	1984	speed-inverse time	-	2-3 min>than 10km time
Housh et al.	1989	Work-time	197±39 W	33.5±15.5 min at 97% of CP
Jenkins & Quigley	1990	Work-time	314.3±27.9 W	6/8 subjects couldn't ride for 30 min
Pepper et al.	1992	distance-time	13.43 $m \cdot s^{-1}$	16.43±6.08 min at CS
McLellan & Cheung	1992	Power-inverse time	265.1±39.3 W	20.5±4.5 min at CP
Jenkins & Quigley	1992	Work-time	255.0±28.4 W	5.7% greater than power sustainable for 40 min
Kranenburg & Smith	1996	Speed-inverse time	292.9±20.8 $m \cdot min^{-1}$	not significantly different from 10km speed

for the entire duration of one hour. At CP the subject group was only able to maintain the intensity for a mean of 33.5 ± 15.5 minutes with 11 of 14 subjects unable to last the entire hour. The model was very useful for predicting time to exhaustion at the three power intensities above CP (time to exhaustion between 2 and 8 minutes). CP is not a power setting which can be maintained indefinitely. Housh et al. (1989) suggest that CP is analogous to but, substantially higher in intensity than the lactate threshold.

Pepper et al. (1992) performed a similar comparison using CS in treadmill running, where speed in running was analogous to power in cycling. The predicted time to exhaustion was calculated using the distance-time model and this time was compared to actual running performance at 70%, 85%, 100%, 115% and 130% of critical speed. Eight of the ten subjects were able to run at 85% CS for the entire 60 minute work bout. At 100% CS, the mean time to exhaustion was 16.43 ± 6.08 minutes. The results of Pepper et al. (1992) indicate that the hyperbolic model was able to predict time to exhaustion at 85% and 115% CS, but over predicted it at 100% and under predicted at 130%. It was also concluded that although CS could not be used to predict the treadmill time which could be maintained without exhaustion, it was still a useful tool for predicting distance running performance. Several studies (Kranenburg & Smith, 1996; Hughson et al., 1984) found that CS correlated strongly with 10 Km running time and that it can be used as an alternative tool for physiological testing of distance runners.

Physiological Components of Critical Power

Critical power has been widely used as a test of both the aerobic and anaerobic energy systems. To determine the usefulness of the CP test for performance monitoring, several studies have attempted to correlate CP with previously known physiological variables. Because CP was defined as an intensity which could be maintained without fatigue, it has been compared most often with the ventilatory and lactate thresholds (Hill, 1993).

Housh et al. (1991) compared the power level at the onset of blood lactate accumulation (OBLA) with CP determined by the work-time model. In 12 male subjects, CP was found to be significantly greater than OBLA ($p<0.05$), although OBLA was the only variable studied which was a predictor of CP by multiple regression ($p<0.05$). Clingeleffer et al. (1994) also found, using the work-time model that CP was significantly different from OBLA ($p<0.05$) in kayakers. Although these two systems are not identical, the physiological variables which contribute to OBLA may also be attributed to CP (Housh et al., 1991). A similar study found that CP was also significantly higher than the power output at the individual anaerobic threshold (McLellan & Cheung, 1992).

In the original study of CP in cycle ergometry, CP was found to be significantly correlated ($r=0.92$)with the ventilatory anaerobic threshold (Moritani et al., 1981). The study also found that oxygen consumption ($\dot{V}O_2$) associated with CP was not significantly different from $\dot{V}O_2$ at the anaerobic threshold. Recent research, however, has found that the power output associated with ventilatory anaerobic threshold is not the same as CP (Hill, 1993). Poole et al. (1988) found CP derived from the power-inverse time model to be 64% higher than the power at the ventilatory aerobic threshold (197W and 120W respectively) defined by Whipp and Mahler (1980). Research indicates that CP is significantly higher than both ventilatory and lactate thresholds, while their correlations are high.

Studies have also examined the anaerobic component of CP. Anaerobic work capacity is defined as a measure of muscle energy reserve (Monod & Scherrer, 1965) and is related to the ability to perform high intensity exercise (Hill, 1993). Anaerobic work capacity has been found to correlate with several tests of anaerobic capacity, including the Wingate (Bar-or, 1987), work in five all out 1-minute maximal efforts (Jenkins & Quigley, 1991), and oxygen debt (Hill & Smith, 1993). Nebelsick-Gullett et al. (1988) found a correlation between AWC and anaerobic capacity measured from a 30 second Wingate test (r=0.74). Other studies have found similar results, although many researchers question the validity of either test to measure anaerobic capacity (Vandewalle et al. 1989). Vandewalle et al. (1989) suggest that a considerable amount of anaerobic energy is still available at the end of the Wingate test, while Hill and Smith (1991) report that the aerobic system contributes between 9 and 28% of the energy used during the test.

Critical power does have an anaerobic component although the method to determine this component has not yet been clearly identified. Moritani et al. (1981) suggested that the AWC was the total amount of work which could be performed using energy sources stored within the muscle (high energy phosphate compounds) and that produced from aerobic breakdown of glycogen. Saltin and Karlsson (1971) state, however, that in high energy work (>CP) only 30% of muscle glycogen is utilized. This must mean that other factors, including lactic acid accumulation and creatine phosphate depletion contribute to muscle fatigue (Housh et al., 1989).

Other Physiological Correlates of Performance

In aerobic exercise, $\dot{V}O_2$ max has been used as the most common measure of aerobic power. Davies and Thompson (1979) found that marathon and ultramarathon running performance could be predicted by a linear regression equation using $\dot{V}O_2$ max. Many other authors have attempted to predict performance from $\dot{V}O_2$ max (Noakes, 1991) although their prediction value tends to decrease as the distance increases. In cross country skiers, $\dot{V}O_2$ max was found to be a better predictor of performance when expressed as $ml \cdot kg^{-2/3} \cdot min^{-1}$ ($\dot{V}O_2^{2/3}$) rather than as $ml \cdot kg^{-1} \cdot min^{-1}$ (Bergh, 1987).

Although $\dot{V}O_2$ max was not found to accurately predict all performance times, peak power output at $\dot{V}O_2$ max was found to be highly correlated (r=0.91) with 20 km performance times in cyclists (Hawley & Noakes, 1992). Another useful indication of aerobic endurance capacity is the lactate threshold which was found to be a strong predictor of performance velocity in cyclists (Coyle et al., 1991).

The determination of lactate and ventilatory thresholds has been open to criticism due to the methodologies used in their determination. Because of this, the maximal lactate steady state (MLSS) as defined by Tegtbur et al. (1993) may provide an objectively determined measure for predicting performance. The MLSS technique produces the same result of speed/power at the lactate minimum regardless of pre test muscle glycogen state. The MLSS test also produces a clear speed at lactate minimum without the need of subjective analysis (Tegtbur et al., 1993). A study comparing black and white South African athletes' running performance (Coetzer et al., 1993) found that the only significantly different physiological parameter between groups was lower blood lactate in the black athletes. This suggests that either decreased lactate accumulation or increased lactate removal significantly contributed to muscle fatigue resistance.

Prediction of performance has also been based upon the composition of skeletal muscle fibers. Tesch and Karlsson (1985) report that endurance athletes have a larger proportion of slow twitch muscle fibers, while anaerobic athletes have a higher proportion of fast twitch muscle fibers in their active muscles. Endurance cyclists with a high percentage of slow twitch muscle fiber were found to have a greater gross efficiency than subjects with a lower percentage of slow twitch fibers (Coyle et al., 1992). A high percentage of slow twitch muscle fibers was also found to be associated with increased performance and power production in a 40km time trial in cyclists (Coyle et al., 1991). Although fiber type analysis provides a useful tool for performance prediction, it requires invasive procedures involving muscle biopsies and painful side effects to the subject. Suter et al. (1993) developed a non invasive protocol by Cybex testing to determine muscle fiber type in the vastus lateralis. The results showed that 51.8% of the variance in muscle fiber type could be explained by relative torque after 55 maximal contractions and by power output at $280^{0}\cdot s^{-1}$ normalized for fat free mass of the thigh (Sovak et al., 1987). Using post muscle biopsies data, two subgroups (subjects with high type II fiber percentage, subjects with high type I fiber percentage) were analyzed using the same regression equation developed on the whole group. Using this subgroup analysis the regression equation was able to account for 70.6% of the actual variance in muscle fiber type.

A combination of these tests and the CP model can be used to produce a very clear picture of an athletes physiological attributes at any given point in time. Both the aerobic and anaerobic systems can be carefully monitored allowing coaches and physiologists the opportunity to identify areas which should be maintained or improved.

CHAPTER 3: METHODOLOGY

Subjects

Twenty one male subjects (26.3 ± 5.2 yrs, 74.0 ± 8.7 Kg) volunteered to participate in this study. All were physically active and were cycling at least 4 hours per week prior to the start of the study. Subjects were recruited from cycling clubs in Calgary. Each subjects was informed of the risks associated with the project and gave written consent to participate. The project was approved by the Faculty of Kinesiology Ethics Committee at the University of Calgary. All speed tests were performed on the subjects' own road bicycles, which were monitored closely for constant air pressure.

The subjects were divided into 2 groups (sprint predominant and endurance predominant) based upon values from the base of the power curve model. Subjects who scored above 75.0 were placed in the sprint predominant group (n=8) and those who scored below 75.0 were included in the endurance predominant group (n=13).

Maximal Oxygen Consumption

Subjects performed an incremental exercise test to exhaustion to determine $\dot{V}O_2$ max and minimum speed at $\dot{V}O_2$ max. Testing was performed on Kreitler rollers allowing each subject to ride on their own road bikes. The rollers were connected to a computer to provide subjects with their current speed, average speed and distance traveled. Ventilatory expired air was measured using a Horizon MMC metabolic cart and heart rate was monitored by a Polar heart rate monitor and both were recorded every 30 seconds.

After a light warm-up subjects began cycling at 25 $km{\cdot}h^{-1}$. The speed was increased by 2 $km{\cdot}h^{-1}$ every 2 minutes until the point of ventilatory threshold II. The ventilatory threshold was determined as the speed at which there was a nonlinear increase in ventilation relative to both $\dot{V}O_2$ and $\dot{V}CO_2$ (Skinner & McLellan, 1980). After this point, the speed was increase by 1 $km{\cdot}h^{-1}$ every minute until volitional fatigue. The speed at which $\dot{V}O_2$ max first occurred was used as the minimum speed at $\dot{V}O_2$ max.

Relative $\dot{V}O_2$ max was calculated using two different formulas. The traditional $\dot{V}O_2$ max value was calculated by dividing absolute $\dot{V}O_2$ ($ml{\cdot}min^{-1}$) by body weight (kg). A second variable was calculated using a correction factor for body weight where the weight of each subject was raised to the power of two thirds. This new weight was then used to calculate the relative $\dot{V}O_2$ max scores ($ml{\cdot}kg^{-2/3}{\cdot}min^{-1}$). Oxygen pulse ($O_2$ pulse) was also calculated from the $\dot{V}O_2$ max data as the maximal amount of O_2 consumed for each heart beat. This was calculated by dividing the absolute $\dot{V}O_2$ max ($ml{\cdot}min^{-1}$) by HR max ($b{\cdot}min^{-1}$).

Critical Speed Tests

Each subject was required to perform 7 maximal effort cycling tests designed to elicit exhaustion between 30 seconds and 40 minutes. Subjects rode on their own road bikes which were connected to a computer data acquisition system via Kreitler rollers. Subjects were permitted to choose their own speed and cadence for each trial. Heart rate of each subject was monitored by a Polar heart rate monitor and time to fatigue was recorded with a stop watch.

The critical speed tests were based on fixed distances of 500m, 1000m, 1500m, 2500m, 4500m, 10km, and 20km which were chosen to elicit finish times of 35 ± 5 seconds, 60 ± 5 seconds, 110 ± 10 seconds, 3.5 ± 0.25 minutes, 7.5 ± 0.5 minutes, 15 ± 1.0 minutes, and 33 ± 2 minutes. The order of the tests were randomized with one test performed per day.

Critical Speed Analysis

Critical speed was determined by modeling the time to cover a specific distance or performance speed. CS was determined from the distance-time model, speed-inverse time model, hyperbolic model and the three-parameter nonlinear model. The linear models were estimated using Microsoft Excel and nonlinear models using Sigmaplot (SPSS). The data was also fit to the power curve and logarithmic models (Microsoft Excel).

Using the speed-inverse time model, times were separated into three segments to produce three separate linear regression equations. All data points were examined to determine which combination of points produced the best regression lines. The first regression line was of all distances, whose time for a distance lay below 2.5 minutes, the second regression line was for distances between 2.5 minutes and 15 minutes and the third regression line was of distances covered in 15 minutes and longer.

Performance Criterion

All subjects completed a 40km time trial on the Kreitler rollers. The speed of this time trial was compared to that predicted from each of the models.

Determination of Maximal Lactate Steady State

The determination of MLSS was performed using the subjects own bike and Kreitler rollers. To induce lactic acidosis, subjects from the endurance predominant group performed a 3 minute ride at 3 minute CS pace determined from the distance-time model, while subjects in the sprint predominant group performed a 2.5 minute ride at 3 minute CS pace. After five minutes of rest, six incremental, progressive rides of 4 minutes were performed at 78, 84, 88, 92, 96, and 100% of CS. The CS was determined as the slope of the distance-time model. Lactate samples were taken by the finger prick method at 4 minutes and 30 seconds of the rest period and during the last 30 seconds of each progressive 4 minute interval. Lactate samples were analyzed by a 1500 YSI lactate analyzer.

The relationship between blood lactate and speed was fitted to a second degree polynomial curve. Maximal lactate steady state was determined as the speed at the minimum point of the curve.

Maximal Instantaneous Power

Instantaneous power was calculated from a series of 6 second sprint cycle tests. On an electronic cycle ergometer, subjects performed 5 trials of 6 seconds to determine a force-velocity profile. Subjects received a 5 minute warm up and had 3-5 minutes of rest between trials. The first test was performed at 0.93 Newtons (N) and each subsequent resistance was chosen to elicit a velocity range of 7.5 - 15 $m{\cdot}s^{-1}$ in each of the 5 trials. A linear regression to the equation $R=mV + R_0$ was performed on the results, where R is the resistance, V is the velocity in $m{\cdot}s^{-1}$, and R_0 is the intercept. The optimal resistance was calculated as $0.5R_0$. Peak power was then calculated at the optimal resistance using both instantaneous data and data averaged over one second. Relative peak power was also calculated by normalizing for individual body weight.

Fiber Type Estimation

Fiber type was estimated by a non-invasive protocol developed by Suter et al. (1993) utilizing Cybex testing. Using a Cybex II dynamometer, subjects performed 55 maximal knee extensor contractions at $90^0{\cdot}s^{-1}$. The mean torque of contractions 53-55 was expressed as a percentage of the highest torque measured during the test (T^{55}). Subjects also performed four maximal effort knee extensor contractions at $280^0{\cdot}s^{-1}$. Power was calculated as the product of peak torque and the angular speed in radians. Peak power was normalized for fat free mass of the thigh (P^{280}/FFMT). The percentage of type II fibers was given by the equation:

Type II fibers = $52.239 - 0.533(T^{55}) + 0.512(P^{280}/FFMT)$.

Anthropometric Measurements

Measurements included 56 directly measured parameters at sites proposed by Ulbrichova (1977) and Pollock et al. (1982). The measurements were composed of body mass, height, 9 breadths, 14 girths, 16 lengths and 15 skinfolds. Body mass was measured using a medical scale and height was measured with a GPM Swiss made anthropometer. Girths and lengths were measured with a Lufkin steel tape and skinfolds were measured with a harpenden caliper. The variables of fat percentage, muscle mass, fat:muscle ratio (F:M) and fat free volume of the thigh were calculated according to the methods of Sovak and Hawes (1987).

Table 4. Summary of tests.

Test	Description
$\dot{V}O_2$ max and speed at $\dot{V}O_2$ max	incremental test using 2 minute stages until VT2, 1 min thereafter
Critical Speed	7 CS tests from 500m to 20 km
Maximal lactate steady state	Induced lactic acidosis followed by six, 4 min increments between 78-100% CS
Instantaneous Power	6 second all out sprint on power bike
Fiber type determination	Cybex testing - $90^0 \cdot s^{-1}$, $280^0 \cdot s^{-1}$
Anthropometry	% body fat, lean muscle mass, fat free mass of the thigh
Criterion Test	40km time trial

Statistical Analysis

The linear and nonlinear regression lines of the CS data were tested for their fit to the data set using r^2 analysis. One way analysis of variance with repeated measures was used to determine the relationship between the CS estimates derived from each model. Graphical analysis was used to identify variations in CS estimates for each individual.

For each linear component of the segmented speed-inverse time model, simple linear regression was used to measure the linear relationship with each predictor variable. The simultaneous effect of the predictor variables was analyzed using manual stepwise multiple regression starting with the strongest predictor variable from the simple linear regression analysis. The final equation identified which variables made the most significant contribution to the model. Each predictor variable was also analyzed by t-tests between endurance predominant and sprint predominant athletes to determine group differences. For all tests the significance level was set at $p<0.05$.

CHAPTER 4: RESULTS

The results are presented in five major sections. The first section outlines the physiological characteristics of the total subject group, the second section presents a comparison of CS estimates derived from the various critical speed models, the third section presents the linear and multiple regression analysis, the fourth section presents the power curve and logarithmic models and the fifth section examines the physiological characteristics and models based on analysis of sprint predominant and endurance predominant subgroups. The raw data for all subjects is presented in Appendix D.

Physiological Characteristics

The means and standards deviation (±SD) of the physiological variables tested are presented in Table 5. The $\dot{V}O_2$ max values for the group ranged from 47.7 to 73.8 $ml \cdot kg^{-1} \cdot min^{-1}$ with a mean of 57.7 ± 6.1 $ml \cdot kg^{-1} \cdot min^{-1}$ and occurred at a mean speed of 40.9 ± 2.3 $km \cdot h^{-1}$. During the MLSS test, the mean lactate value achieved under the initial conditions of inducing lactic acidosis was 11.4 ± 2.2 $mmol \cdot L^{-1}$. The mean r^2 values from the second order polynomial for the fit of the lactate curve from the progressive MLSS test was 0.96 ± 0.03 (Appendix F). The mean speed at MLSS was 31.4 ± 2.0 $km \cdot h^{-1}$ where the mean lactate value was 3.6 ± 1.3 $mmol \cdot L^{-1}$.

Table 5. Physiological characteristics of all subjects in the study. Data is reported as means and standard deviations for the whole group.

Variable	Mean	SD
$\dot{V}O_2$ max (ml·kg^{-1}·min^{-1})	57.7	6.1
$\dot{V}O_2^{2/3}$ max (ml·kg$^{-2/3}$·min^{-1})	241.0	20.3
O_2 Pulse (ml·beat^{-1})	22.5	1.9
Speed at $\dot{V}O_2$ max (km·h^{-1})	40.9	2.3
MLSS speed (km·h^{-1})	31.4	2.0
Peak instantaneous power (W)	2230.4	397.8
1s peak power (W)	1284.9	245.4
Relative peak instantaneous power (W·kg^{-1})	30.1	3.1
Relative 1s peak Power (W·kg^{-1})	17.3	2.1
FFVT (mL)	8907	1289
Fat:Muscle	291	83
% body fat	13.8	3.5
% type II fibers	43.1	9.0

The mean peak instantaneous power was 2230.4 ± 397.8 W, compared to 1284.9 ± 245.4 W when averaged over 1 second. The mean relative peak instantaneous power was 30.1 ± 3.1 W·kg^{-1}, while the mean relative peak power averaged over 1 second was 17.3 ± 2.1 W·kg^{-1}. The rank order of these four variables was found to be similar with more differences occurring between relative and absolute values than between instantaneous and 1 second averaged values (Table 15). The fiber type of the subjects is presented as a percentage of type II muscle fibers, and ranged from 31% to 59%.

Model Analysis

Critical Speed Time Trials

For the distance of 500m, 1000m, 1500m, 2500m, 4500m, 10km, and 20km the mean times to finish were: 33.3 ± 3.2 s, 75.5 ± 5.9 s, 2.1 ± 0.1 min, 3.7 ± 0.2 min, 7.0 ± 0.5 min, 16.6 ± 1.0 min, and 34.6 ± 3.6 min respectively.

Critical Speed Models

Critical speed was determined using five different models, from which a significant global difference was found in their values (Appendix E) by one way ANOVA with repeated measures ($p<0.001$). The individual differences in each model are clearly evident from the curve fitting analysis of subject 21 (figure 4).

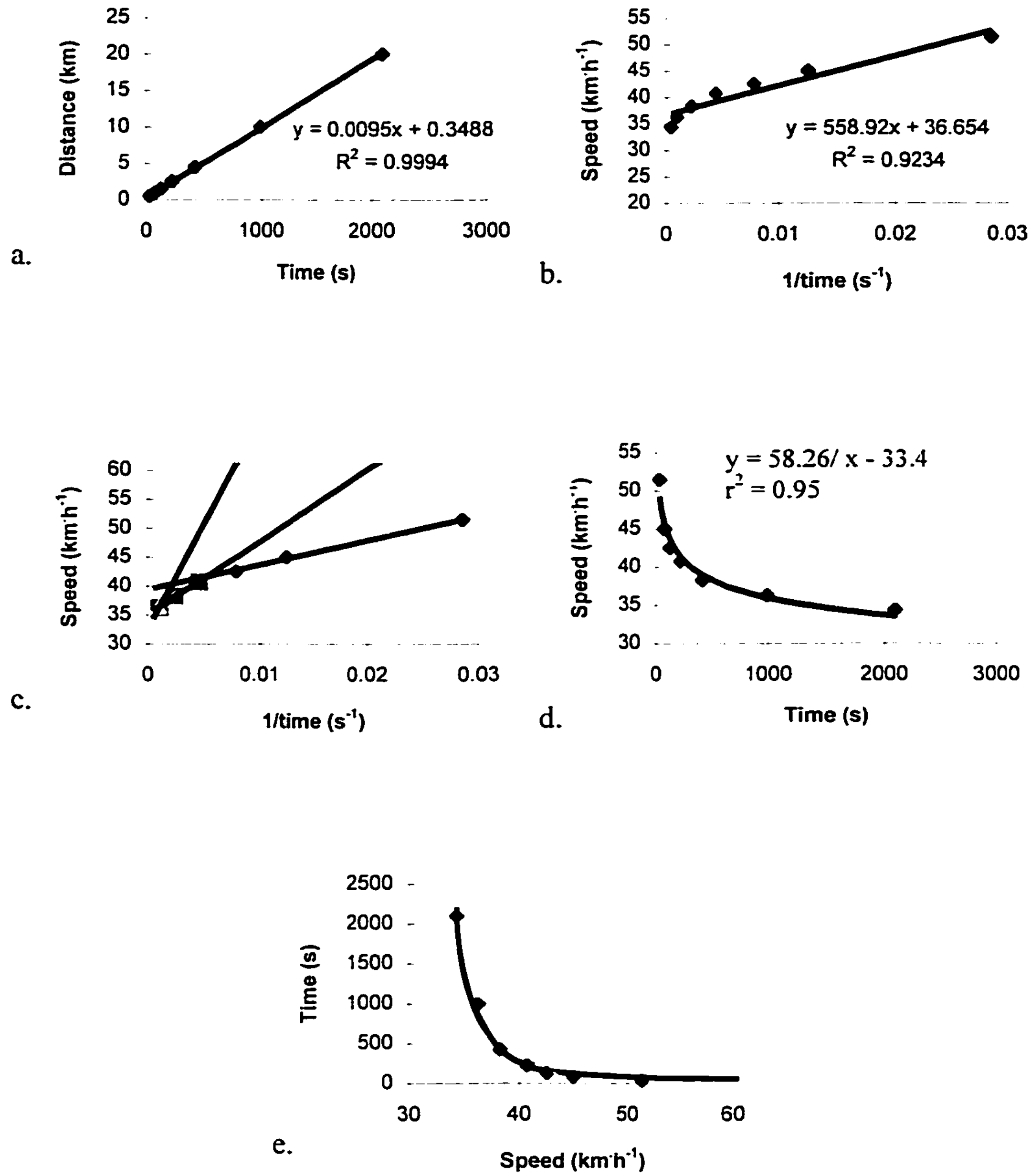


Figure 4. Regression analysis for the critical speed models fit to the data of subject 21. CS estimates were: a) distance vs. time = 34.2 km·h^{-1} b) speed vs. 1/time = 36.7 km·h^{-1} c) speed vs. 1/time segmented: short = 39.4 km·h^{-1}, medium = 35.2 km·h^{-1}, long = 32.6 km·h^{-1} d) two-parameter hyperbolic model = 33.4 km·h^{-1} e) three-parameter hyperbolic model was 32.7 km·h^{-1}.

Pairwise significant differences were found between all models (Table 6) with the exception of one case. The speed of the 3-segmented long model was not significantly different from the speed of the three-parameter hyperbolic model. The highest estimate of CS was produced by the 3-segmented short model, while the lowest estimate was produced by the long model. The rank order of the CS estimates (Table 6) was also consistent with the order of values found for each subject on an individual basis. In three cases however, CS long was higher than CS medium (subjects 1, 5, 18).

Critical speed estimates from all models were compared to the performance speed of the 40 km criterion ride. This was done to determine which model most accurately predicted 40 km pace in cyclists. All CS estimates were found to be significantly different than 40 km speed (Table 6) with the exception of the 3-segmented long model ($p = 0.63$), and the 3- parameter hyperbolic model ($p = 0.32$) .

Table 6. Critical speed estimates from each of the critical speed models and the average speed from the 40 km criterion ride.

Model	CS ($km \cdot h^{-1}$)	SD	r^2	SD	Range
Distance vs. time	34.3	2.3	1.00	0.00	1.00-1.00
Speed vs. 1/time	36.8	2.5	0.91	0.04	0.83-0.96
Speed vs. 1/time - Short	40.8	2.8	0.97	0.04	0.84-1.00
Speed vs. 1/time - Medium	35.0	2.4	0.96	0.04	0.89-1.00
Speed vs. 1/time - Long*	33.2	2.7	1.00	0.00	1.00-1.00
2-Parameter hyperbola	33.8	2.4	0.96	0.02	0.91-1.00
3-Parameter Hyperbola	33.4	2.5	0.99	0.01	0.93-1.00
Actual 40 km speed	33.3	2.4	-	-	-

*regression line determined from 2 points only.

The three segmented model estimates of CS were compared to the speeds from each CS time trial and the speed at $\dot{V}O_2$ max. A global difference was found between each of the time trials and the three estimates of CS ($p<0.001$). The seven speed values from the time trails and the three CS estimates were all significantly different, with three exceptions. The speed estimated by the 3-segmented short model, the speed from the 2500m time trial, and the speed at $\dot{V}O_2$ max were all not significantly different from each other. The speed estimated from the medium model was not significantly different than the speed of either the 10000m ($p=0.098$) or the 20000m ($p=0.551$) time trials. The speed predicted by the medium model however, was 0.69 $km \cdot h^{-1}$ closer to the speed from the 20000m time trial, than that of the 10000m time trial.

The equation from the 3-segmented medium model was used to calculate the projected duration of exercise for speed at $\dot{V}O_2$ max. Projected times ranged between 115 to 291 seconds with a mean time of 222 ± 32 seconds.

Segmented Model Intercepts

Using the equations generated from the segmented model, two points of intersection for were calculated for the three lines. The intersection points for the short and medium models was found at 155 ± 40 seconds. The intersection point for the medium and long models was found at a mean time of 902 ± 212 seconds.

Regression Analysis

Simple Linear Regression Analysis

Results of the linear regression analysis are presented in Table 7. The variable which showed the most significant relationship with the short model was speed at $\dot{V}O_2$ max ($p<0.001$). Maximum lactate steady state, muscle fiber type and O_2 pulse also had significant relationships ($p<0.001$, $p=0.021$, and $p=0.008$) with the short model. The anthropometric variables did not show significant individual relationships with either of the three models. Three out of the four peak power variables were significantly related to the short model, including peak instantaneous power ($p=0.018$), peak power averaged over 1 second ($p=0.011$) and relative peak power averaged over 1 second ($p=0.049$).

The two variables with the strongest linear relationships to the medium model were MLSS and speed at $\dot{V}O_2$ max ($p<0.001$ for both): Oxygen pulse and $\dot{V}O_2^{2/3}$ were also significantly related to the medium model ($p=0.003$ and $p=0.019$). The same four variables were also significantly related to the long model ($p<0.001$, $p<0.001$, $p=0.001$, and $p=0.042$).

The variable MLSS accounted for 46.5, 89.4, and 79.1% of variation in the short, medium and long models respectively. Muscle fiber type accounted for 26.3% of the variation in the short model, while speed at $\dot{V}O_2$ max accounted for 69.7% of the variation in this model. The speed at $\dot{V}O_2$ max accounted for 77.4% of the variation in the medium model and 59.0% of the long model. The three power variables which showed significant individual relationships to the short model accounted for the following percentages of the model: peak instantaneous power (27.3%), peak power averaged over

1 second (31.0%) and relative peak power averaged over 1 second (19.8%). The variable O_2 pulse accounted for 31.5, 38.0 and 43.8% of the variation in the short, medium and long models respectively. The variable $\dot{V}O_2^{2/3}$ accounted for 25.8% of the medium model and 20.0% of the long model. These percentages were all determined by the r^2 values from the linear regression analysis.

Table 7. Linear regression analysis between the 3 segmented models of critical speed and each of the physiological parameters.

	Short			Medium			Long		
Parameter	**Slope**	**Constant**	**p-value**	**Slope**	**Constant**	**p-value**	**Slope**	**Constant**	**p-value**
$\dot{V}O_2$ max	-0.044	43.645	0.629	0.107	28.830	0.128	0.099	27.480	0.215
$\dot{V}O_2^{2/3}$ max	1.854	165.53	0.272	4.327	89.468	0.019*	3.407	128.01	0.042*
O_2 Pulse	0.397	6.335	0.008*	0.502	4.896	0.003*	0.484	6.477	0.001*
$\dot{V}O_2$ speed	1.027	-1.242	0.000*	1.040	-7.593	0.000*	1.020	-8.632	0.000*
MLSS	0.886	13.143	0.001*	1.180	-2.000	0.000*	1.246	-5.966	0.000*
Inst Power	0.003	34.241	0.018*	0.001	33.175	0.489	0.002	28.705	0.152
1s Power	0.005	34.201	0.011*	0.002	32.746	0.374	0.003	29.266	0.184
RP inst	0.298	32.129	0.075	0.108	32.002	0.520	0.227	26.592	0.221
RP 1s	0.499	32.436	0.045*	0.226	31.325	0.375	0.229	28.381	0.309
FFVT	0.001	34.641	0.161	0.000	32.867	0.517	0.001	26.063	0.063
Fat:Muscle	0.007	39.100	0.292	-0.002	35.705	0.802	-0.002	34.060	0.754
% Fat	0.188	38.505	0.216	-0.032	35.679	0.832	-0.036	33.908	0.829
% Type II	0.138	35.069	0.021*	0.056	32.840	0.343	0.030	32.114	0.668

*indicates a significant relationship between the variable and the model.

Multiple Regression Analysis

All of the physiological variables were included in a manual stepwise forward multiple regression procedure. Variables with the highest r^2 from the simple regression and those which were previously known to contribute to similar performance time domains were included first. The first variable included in the regression analysis of the short model was speed at $\dot{V}O_2$ max, while for the medium and long models it was MLSS. For the short model, the final equation included the variables: speed at $\dot{V}O_2$ max, and peak instantaneous power averaged over 1 second. These variables accounted for 79.15% of the variation in the short model ($p<0.001$). The predicted equation obtained using this analysis was:

CS Short = 0.9536*(Speed at $\dot{V}O_2$ max) + 0.003297*(power-1s) - 2.5601 **[1]**

The equation for the medium model included the variables: MLSS and speed at $\dot{V}O_2$ max which accounted for 91.37% of the variation in the medium model ($p<0.001$). The predicted equation obtained using this analysis was:

CS Medium= 0.8926*(MLSS) + 0.3184*(Speed at $\dot{V}O_2$ max) - 6.0768 **[2]**

The equation for the long model was improved by the addition of FFVT and $\dot{V}O_2^{2/3}$ max to the MLSS variable. The final equation for the long model predicted by the multiple regression analysis was:

CS Long= 0.8982*(MLSS) + 0.04478($\dot{V}O_2^{2/3}$max) + 0.008469*(FFVT) - 13.4196 **[3]**

which accounted for 87.54% of the variation ($p<0.001$).

Using equations 1, 2 and 3, CS short, medium and long were calculated for each subject. The relationship between the predicted CS values and the real CS values were compared graphically to the line of identity (Figures 5,6,7). Each graph shows that the relationship is very close to the line of identity. The mean predicted values were not significantly different than the actual means of the three models.

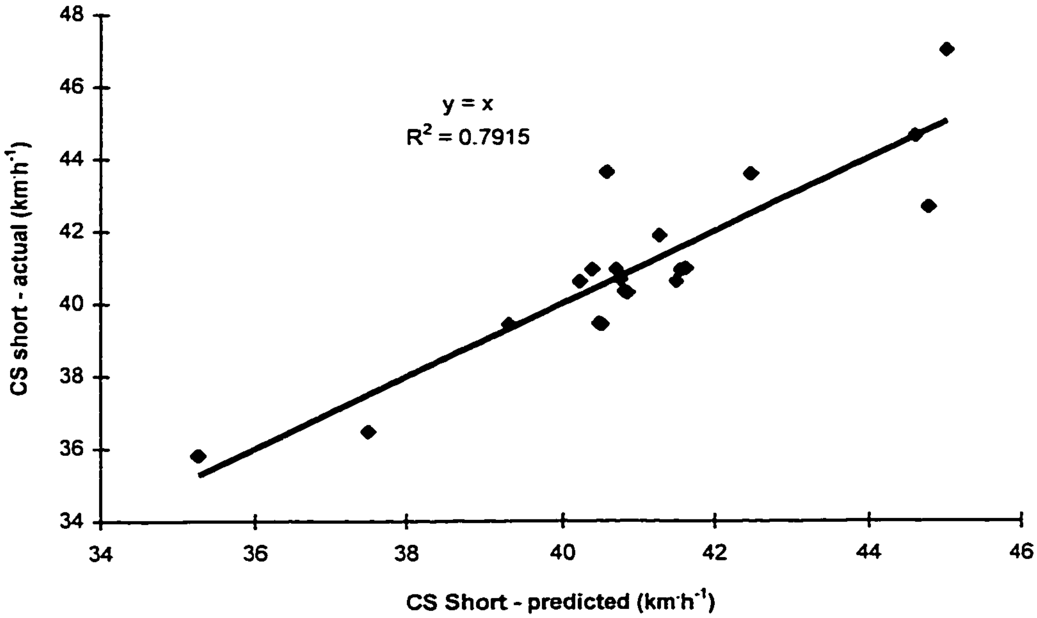


Figure 5. The relationship between CS short and CS short predicted from the equation CS short = 0.9536*(Speed at $\dot{V}O_2$ max) + 0.003297*(power-1s) - 2.5601.

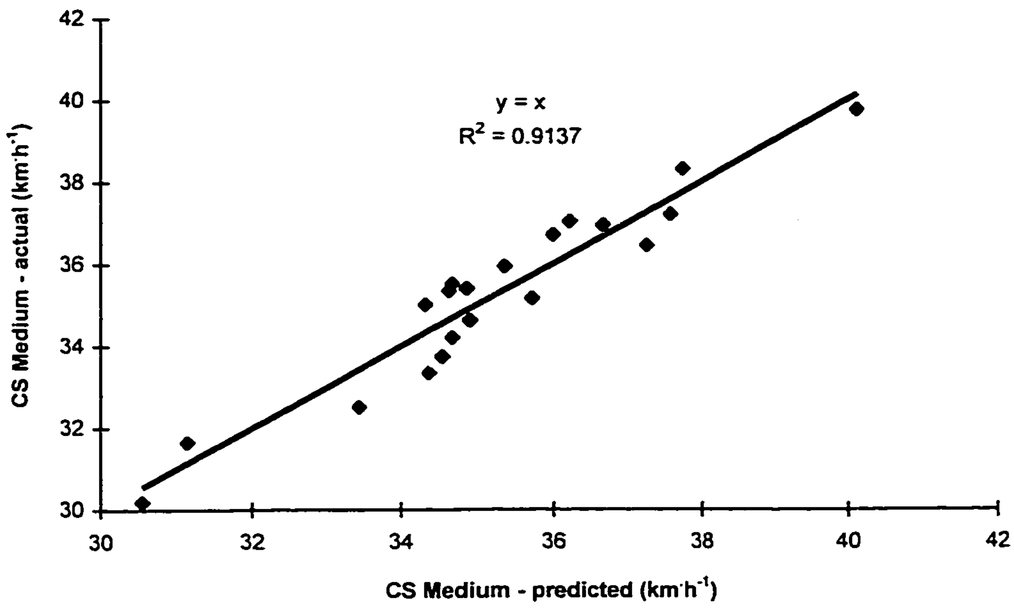


Figure 6. The relationship between CS medium CS medium predicted from the equation CS Medium = 0.8926*(MLSS) + 0.3184*(Speed at $\dot{V}O_2max$) - 6.0768.

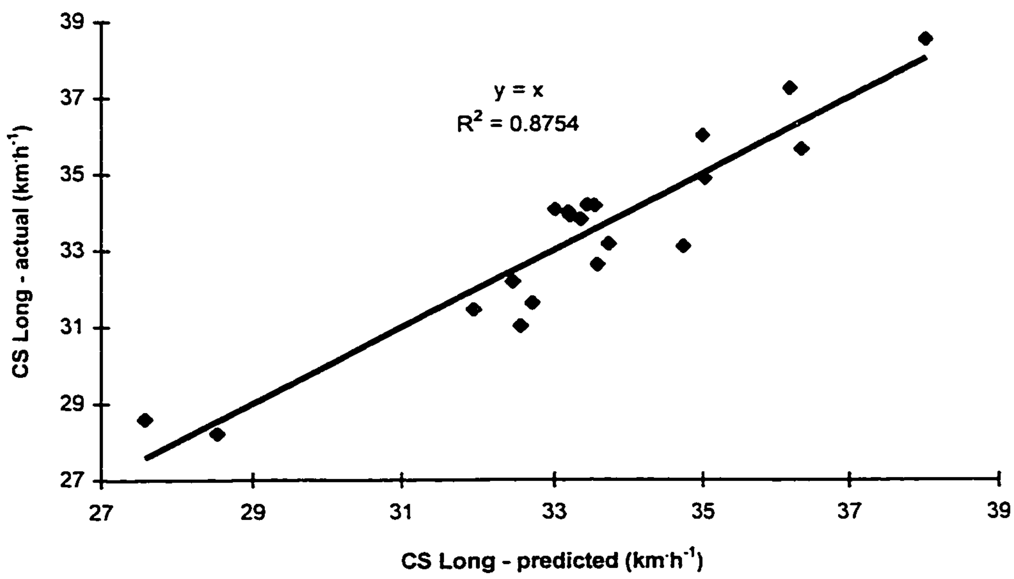
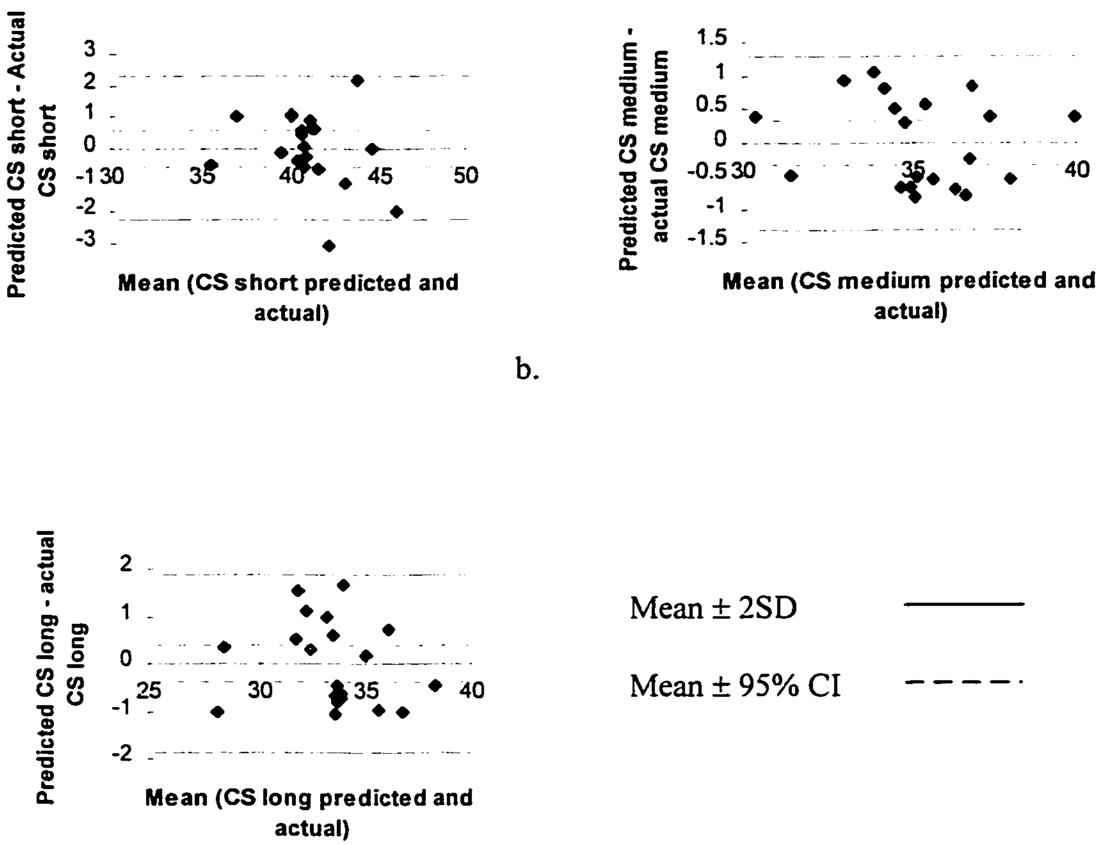


Figure 7. The relationship analysis between CS long and CS long predicted by the equation CS long = 0.8982*(MLSS) + 0.04478*($\dot{V}O_2^{2/3}max$) + 0.008469*(FFVT) - 13.4196 .

Bland-Altman plots were used to determine the agreement between the actual critical speed values and those predicted by the three models. These graphs are used to determine if the relationship is significantly different from the line of identity (Bland and Altman, 1986). The values from the three predicted equations show strong agreement to the actual CS values (Figure 8). The linear equation for all three lines was y=x, and the value zero lay within the 95% confidence interval of each plot.



a. b.

c.

Figure 8. Bland-Altman plots of agreement between the actual critical speed estimates and those predicted from the multiple regression models. a) short b) medium c) long.

The Power Curve and Logarithmic Models

Using the same data as the CS models, points were fit to the power curve and logarithmic models. The subject pool was divided into two groups using the base from the power curve as the limiting factor. All subjects with a base value above 75.0 were considered sprint predominant athletes (group 1) and all subjects with base values below 75.0 were considered endurance predominant athletes (group 2). Subjects 1-8 made up the sprint predominant group and subjects 9-21 made up the endurance group. The difference in characteristics between endurance and sprint cyclists can be easily visualized using this model (Figure 9). Sprint predominant cyclists show a large peak in speed with a large decay in the speed as time increases. Endurance predominant cyclists, however, show a much smaller peak speed with the ability to maintain a larger percentage of their peak speed for a long duration.

Values from the logarithmic model ranged from -5.27 to -10.48. The best sprint predominant cyclists show log values below -9.00 while the best endurance predominant cyclists show log values above -7.00 (Figure 10).

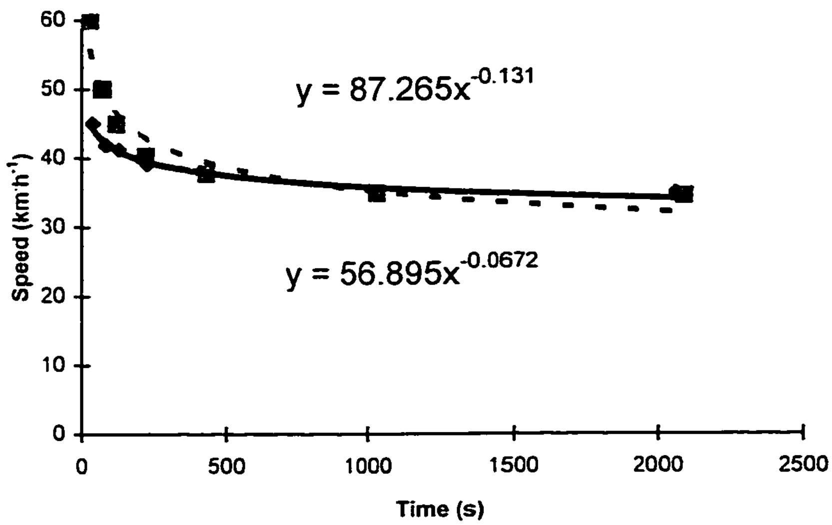


Figure 9. The relationship between power curve fits to a sprint predominant vs. an endurance predominant cyclist. The dashed line represents the sprint predominant cyclist (Subject 5) and the solid line represent the endurance predominant cyclist (Subject 18).

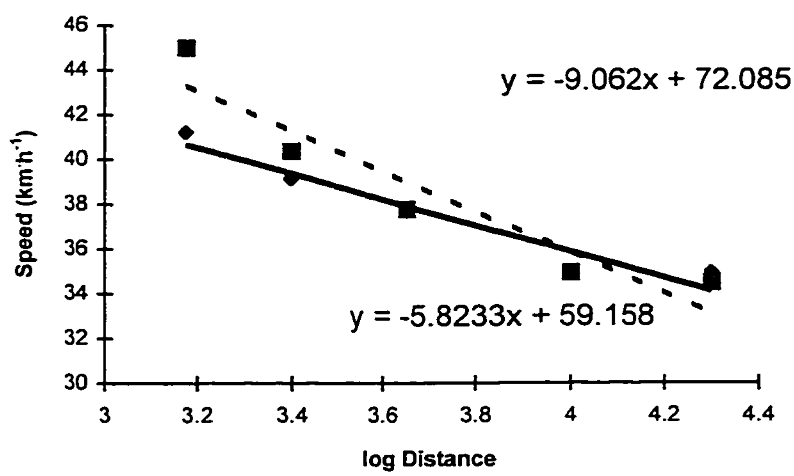


Figure 10. The relationship of logarithmic model values between an endurance predominant and a sprint predominant cyclist. The value used for the model is the slope of the line. The dashed line represents the sprint predominant cyclist (subject 5) and the solid line represent the endurance predominant cyclist (subject 18).

Values derived from the power curve and logarithmic models were found to be significantly different between the two groups (Table 8). From the power curve model, the base was significantly higher in the sprint predominant group by an average of 17.41 ($p<0.001$). The exponent value from this model was also significantly different ($p=0.003$) with the endurance predominant group values being less negative by a mean of 0.035. From the logarithmic model, values were found to be more negative in the sprint predominant group with a significant difference of 2.35 ($p<0.001$).

Table 8. Comparison of the values from the logarithmic and power curve models between the endurance predominant and sprint predominant groups.

Model	Sprint Predominant Mean	SD	Endurance Predominant Mean	SD
Log	-9.41*	0.62	-7.05	1.16
Base	86.01*	4.46	68.60	4.70
Exponent	-0.1243*	0.0088	-0.0889	0.0277

* indicates significant difference

Subgroup Analysis: Endurance and Sprint Predominant Cyclists

Physiological Differences

The means of the physiological characteristics of the sprint and endurance predominant groups are presented in Table 9. Of the 13 physiological variables compared between groups, five were found to be significantly different. The muscle fiber type of the sprint group was found to be composed of 13% more type II muscle fibers compared to the endurance group and was significantly different ($p<0.001$). The cardiovascular variables did not show any significant differences between the two groups.

Table 9. Comparison of the physiological characteristics of the endurance and sprint predominant cyclists.

Physiological Variable	Sprint Predominant Mean	SD	Endurance Predominant Mean	SD
$\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$)	55.2	5.1	59.2	6.38
$\dot{V}O_2^{2/3}$ max ($ml \cdot kg^{-2/3} \cdot min^{-1}$)	237.2	17.1	243.5	22.38
O_2 Pulse ($ml \cdot beat^{-1}$)	23.0	1.0	22.2	2.32
Speed at $\dot{V}O_2$ max($km \cdot h^{-1}$)	41.9	1.4	40.3	2.59
MLSS speed ($km \cdot h^{-1}$)	31.6	1.02	31.25	2.43
Power-inst (W)	2511.7*	403.2	2057.3	289.22
Power-1s (W)	1460.2*	256.5	1177.0	170.04
Relative Power-inst ($W \cdot kg^{-1}$)	31.3	3.6	29.3	2.66
Relative Power - 1s ($W \cdot kg^{-1}$)	18.2	2.5	16.8	1.59
FFVT (mL)	9372	1125	8621	1341
Fat:Muscle	358*	87	249	46
% body fat	16.8*	3.6	11.9	1.9
% type II fibers	51.5*	5.5	38.0	6.4
Weight (kg)	80.2*	7.1	70.2	7.4

* indicates significant difference between the two groups.

Of the anthropological variables, the percentage of body fat and Fat:Muscle ratio values were found to differ significantly between the endurance and sprint predominant groups ($p<0.001$, and $p=0.001$). The sprint group had a significantly greater percentage of body fat by 4.9% and the Fat:Muscle ratio of the sprint group was also significantly higher than that of the endurance group by a mean of 109.

From the instantaneous power data, it is apparent that the sprint predominant group was significantly more powerful than the endurance predominant group. Of the four peak power variables, two were significantly different. Peak instantaneous power and peak power averaged over 1 second were found to be significantly different between the two groups. Peak instantaneous power was 454 W greater (p=0.007) and peak power averaged over 1 second was 283 W greater in the sprint predominant group (p=0.007). Relative power values were not found to be significantly different, although in both cases the mean relative power of the sprint predominant group was higher than that of the endurance predominant group (Table 9).

Critical Speed Models

The CS short value was found to be significantly higher by 2.7 $km{\cdot}h^{-1}$ in the sprint predominant group (p= 0.06) compared to the endurance predominant group. There were no other significant differences found from the estimates of the CS models between the two groups (Table 10).

Table 10. Comparison of CS estimates of all models between the sprint and endurance groups.

Model	Sprint Predominant CS ($km{\cdot}h^{-1}$)	SD	Endurance Predominant CS ($km{\cdot}h^{-1}$)	SD
Distance vs. time	34.5	1.3	34.1	2.8
Speed vs. 1/time	37.6	1.4	36.4	2.9
Speed vs. 1/time - Short	42.4*	2.3	39.7	2.6
Speed vs. 1/time - Medium	35.5	1.4	34.8	2.9
Speed vs. 1/time - Long	33.4	1.9	33.1	3.1
2-Parameter Hyperbola	34.1	1.4	33.7	2.9
3-Parameter Hyperbola	33.7	1.7	33.2	2.9

* indicates significant difference between the two groups.

CHAPTER 5: DISCUSSION

Critical Speed Models

The present study found that all models except the 3-segmented long model and the 3-parameter hyperbolic model, produced critical speed estimates that were significantly faster than the criterion performance of a 40 km time trial. Gaesser et al. (1995) compared critical power estimates from work vs. time; power vs. inverse time; 2-parameter hyperbolic and 3-parameter hyperbolic models, and demonstrated that the 3-parameter hyperbolic model produced the lowest CP estimate. The present study confirms that the 3-parameter hyperbolic model produces the lowest CS estimate and also demonstrates that the estimated speed (33.4 $km{\cdot}h^{-1}$) was not significantly different from a 40 km time trial (33.3 $km{\cdot}h^{-1}$). Furthermore, using the new 3-segmented model, the speed vs. inverse time long model (33.2 $km{\cdot}h^{-1}$) also predicted 40 km time trial speed. Thus a linear model, determined from maximum efforts between 17 minutes and 35 minutes duration can predict long duration performance.

The 3-parameter nonlinear model was developed to reduce the overestimation of CP produced by the models currently in use. The 3-parameter model differs from the 2-parameter model by removing the requirement that the time asymptote be at zero. This adjustment improves the model by providing significantly lower estimates of CP (Morton, 1996) or CS. It also suggests that maximal instantaneous power is not infinite as time approaches zero and that the anaerobic work capacity need not be fully depleted at exhaustion. The present study, as well as Gaesser et al. (1995) provide further support for this model as a predictor of endurance performance.

Accuracy and Sensitivity of Fit to the Models

The present study used a series of seven trials between 33 seconds and 35 minutes to calculate CS. Using this wide range of times, the goodness of fit of each model was investigated using r^2 as a measure of association. While the mean r^2 values of the distance vs. time model were 1.00 ± 0.00, this model produced CS estimates similar to that of the medium segmented model, and may only predict speeds which would be sustainable for distances in the range of 20 km or 35 minutes. It was apparent from the r^2 values of the speed vs. 1/time model that it did not fit at all to a model covering such a wide range of times. The r^2 values ranged from 0.83 to 0.96. The CS estimates from this model were even higher than those predicted by the distance vs. time model.

The two non-linear models produced the best fit to the data using all 7 points with the 3-parameter hyperbolic model having the best fit to the data (r^2= 0.99 ±. 0.01). As discussed previously, this model also produced a close estimate of a speed which could be maintained over 40 km. The 2-parameter hyperbolic model also fit the data very well (r^2 = 0.96 ± 0.02), but the 2-parameter model estimates were consistently greater than those of the 3-parameter model. Of the models which use the comprehensive series of data points to predict CS, the 3-parameter hyperbolic model ranked first in its ability to estimate a speed which could be maintained for 40 km, and its ability to fit the data.

The r^2 values from the 3 segments of the segmented model showed that this model fit each segment of the data very well. Because the long model was composed of only 2 data points, it always had an r^2 value of 1.00. The r^2 values from these three models were all much better than those produced using the speed vs. 1/time model as a whole. This suggests that the speed vs. 1/time model is better when used in discrete time segments rather than covering a broad range of times.

The results of the segmented model analysis also support the findings of Bishop et al. (1998) who found that critical power estimation was dependent upon the duration of the predictive tests used to form the model. Models using shorter predictive trials were found to produce higher estimates of CP using the work vs. time model. In the present study, the 3-segmented models produced higher estimates of CS when they were composed of shorter time trials. The data in the present study was also analyzed using the distance vs. time model as Bishop et al. (1998). Using the five time trials from 1000 m to 10 km, CS was calculated using trials 1,2,3 (CS_{123}); 1,3,5 (CS_{135}); 3,4,5 (CS_{345}). CS_{123} was found to be significantly different from both CS_{135} and CS_{345}, however, CS_{135} was not significantly different from CS_{345}. These results clearly show that the use of short duration time trials to calculate CS using linear models produces high estimates of CS. Thus, time trial duration should be carefully considered when using critical speed analysis, to ensure that the results of the CS modeling are useful.

Performance Prediction

The segmented model of critical speed found that the speed vs. 1/time model could be used to calculate the performance speed for a cyclist. The speeds predicted by the short, medium and long models were not significantly different than the speeds of the 2500 m, 20 km and 40 km time trials respectively.

The short and medium segmented models were composed of time trials whose distances were approximately 0.5, 0.25 and 0.125 of the distance whose speed they predicted. The segmented long model however consisted of only two time trials whose distances were equal to 0.5 and 0.25 of the prediction distance. Therefore, using at least two distances which are approximately 0.5 and 0.25 times the distance in question, an accurate estimation of the performance speed for that distance may be calculated. The model would be improved with the addition of a third time trial so that the goodness of fit of the line could be judged (Hill, 1993). This third time trial should be set at a distance such that its time remains longer than the intercept between the models. Thus, for the medium model it should be longer than 2.5 minutes and for the long model, it should be longer than 15 minutes. This data contradicts previous recommendations to use time trials within a range of 1 to 10 minutes to calculate CS (Poole et al. 1986). Using the Poole et al. (1986) technique, the CS estimated by the model would only be sustainable over a distance between 15 and 20 km or a duration of 25 to 40 minutes as has been previously reported (Table 11). Thus, the use of short duration time trials may lead the over-estimation of long duration performance such as a 40 km time trial.

Table 11. Metanalysis of exercise time to fatigue at critical speed and critical power from previous research studies.

Reference	Year	Model	Results of performance test at CP or CS
Hughson et al.	1984	speed-inverse time	Under 36 minutes
Housh et al.	1989	Work-time	33.5±15.5 min at 97% of CP
Pepper et al.	1992	distance-time	16.43±6.08 min at CS
McLellan & Cheung	1992	Power-inverse time	20.5±4.5 min at CP
Kranenburg & Smith	1996	Speed-inverse time	34.2 ± 2.5 minutes

Physiological Variables Associated with the 3-Segmented Models

Critical Speed and MLSS

The results from the present study support the findings of several studies which have also found that CP and CS occur at higher power outputs than the anaerobic or ventilatory thresholds. Each of the models used in this study produced CS estimates which were significantly greater than the speed at MLSS. The mean speed of the 40 km time trial was 1.9 $km \cdot h^{-1}$ faster than mean speed at MLSS. Housh et al. (1991) found that CP (230 W) from the work vs. time model was significantly higher than the power output at the lactate threshold (180 W) and using the individual anaerobic threshold methodology, McLellan and Cheung (1992) found that CP estimated from the power vs. 1/time model occurred at a power output which was 13% greater than that of the individual anaerobic threshold. Gaesser et al. (1995) found that the power output at the ventilatory threshold (189 W) was significantly less (4.2%) than CP estimated from the 3-parameter nonlinear model (195 W). In the present study, the speed at MLSS was found to be significantly less (6.0%) than the CS estimated by the 3-parameter nonlinear model.

Poole et al. (1991) also found similar results when comparing CP from the power vs. 1/time model to the ventilatory anaerobic threshold and critical speed in runners was found to occur at a mean speed, 7% above the ventilatory threshold (Kranenburg and Smith, 1996). Critical speed must therefore, represent a speed which will induce lactic acid build-up and eventually lead to fatigue. The time frame at which fatigue occurs was found to be dependent upon the model chosen to calculate CS and the duration of time trials chosen within the model.

The Short Model

Using simple linear regression, seven physiological variables were found to have a significant relationship with the short model. These variables were MLSS, muscle fiber type, speed at $\dot{V}O_2$ max, peak instantaneous power and 1 second averaged power, relative peak power averaged over 1 second, and O_2 pulse. The two variables which were found to significantly contribute to the multiple regression model were speed at $\dot{V}O_2$ max and peak power averaged over 1 second. The speed at $\dot{V}O_2$ max was the strongest single predictor of CS short with an r^2 value of 0.70. This data supports the findings of Nelson et al. (1997) who found that power output at $\dot{V}O_2$ max was significantly correlated with critical power calculated using three short time trials between 30 sec and 90 sec duration. In combination with peak power averaged over 1 second, the r^2 value increased to 0.79, increasing the predictability of the regression model. The contribution of this variable supports the original research hypothesis of an anaerobic variable contributing to the short model. Faster speeds were attained in a short duration by subjects' who could generate a large amount of power. Although, the linear regression between CS short and peak power averaged over 1 second produced an r^2 of 0.31, it was only the fourth best individual predictor of CS short. However, in combination with speed at $\dot{V}O_2$ max, it made the most significant contribution. This segment of the 3-segmented model is suggested to therefore, represent anaerobic-aerobic performance down to 100% $\dot{V}O_2$ max.

The Medium Model

The results of the simple linear regression analysis indicate that there were four variables which were significantly related to the medium model: MLSS; speed at $\dot{V}O_2$ max; O_2 pulse; $\dot{V}O_2^{2/3}$ max. Again, using multiple regression, the variables MLSS and speed at $\dot{V}O_2$ max were found to significantly contribute to the model. MLSS accounted for most of the variation in this model ($r^2 = 0.89$). The addition of speed at $\dot{V}O_2$ max to the multiple regression model improved the r^2 to 0.91. The addition of this variable agrees with the research hypothesis. In the overall model, subjects with both higher MLSS speeds and higher speeds at $\dot{V}O_2$ max would have the highest values estimated from the medium model. Strength in these two areas would therefore lead to strong performance ability for distances in the range of 20 km. The speed at $\dot{V}O_2$ max was a speed which fell within the range of speeds used to calculate the medium model. This variable must therefore have an important affect on the ability of a subject to perform between 2.5 and 15 minutes and predicts performance up to 35 minutes. This model may predict performance down to 89% $\dot{V}O_2$ max (Davies and Thompson, 1979).

The Long Model

The same four variables which produced significant individual linear regressions with the medium model were also significantly associated with the long model. The final model from the multiple regression analysis for the long model included the variables MLSS, $\dot{V}O_2^{2/3}$ max, and FFVT. These results support the research hypothesis that the aerobic variables of MLSS and $\dot{V}O_2^{2/3}$ max would significantly contribute to the long model. It is interesting to note that FFVT is a significant variable. Many of the faster cyclists were more powerful in nature and possessed larger thigh muscle masses. For this reason the model suggests that subjects with a larger FFVT will produce faster performance times in long duration events.

Subjects with strong aerobic ability showed high values for MLSS speed and were able to cycle at higher speeds than less fit individuals. These subjects were therefore able to cycle at higher speeds for the long duration time trials and therefore produced a higher score in the CS long model. This supports the findings of Coetzer et al. (1993) who found that subjects with a smaller accumulation of lactic acid produced better performance times in long distance running events. The long model therefore, represents long duration performance below 89% $\dot{V}O_2$ max.

Cardiovascular Variables

The variables $\dot{V}O_2$ max, $\dot{V}O_2^{2/3}$ max, and O_2 pulse were all calculated from the incremental maximal oxygen uptake test. Of these variables, $\dot{V}O_2^{2/3}$ max was found to be the best predictor of long duration performance. This supports previous findings of Ingjer, (1991) who found that this variable was a strong predictor of performance in cross country skiers. In this study, the variable $\dot{V}O_2^{2/3}$ max was a stronger predictor of 40 km cycling performance than $\dot{V}O_2$max ($r = 0.54$ vs. $r = 0.34$). The subjects used had mean $\dot{V}O_2^{2/3}$ max values below those of world class athletes. However, the group ranged from normal values to just under world class elite standards (Ingjer, 1991). The same standards were met by the group as measured by the variable O_2 pulse. Bhambhani et al. (1994) found that mean O_2 pulse values for a trained population were 23.8 ± 5.1 mL·beat^{-1} while values in the present study were $22.5 + 1.9$ mL·beat^{-1}.

Power Variables

The subjects peak power production in this study fell within the normal range of values previously found for these tests. In this study, the data was measured both instantaneously and averaged over 1 second. The peak power data was found to be significantly related to the short CS model (Table 7). The subjects who performed best on the power tests were able to generate higher speeds in the shorter time trials. The ability to generate high peak power was therefore, found to provide a strong base for short distance cycling events. Furthermore, the two absolute power variables were significantly different between sprint predominant and endurance predominant groups as one would expect.

The Power Curve and Logarithmic Models

The power curve and logarithmic models were used in this study to identify the overall performance characteristics of each subject. Previous research has found that these two models could categorize athletes as either sprint or endurance predominant cyclists. This study was used to validate these findings for cyclists.

The Power Curve

The power curve model was previously used by Nelson et al. (1997) to identify the subjects' performance specialization. The present study found that the base had a stronger relationship with short duration peak power, than with overall performance specialization. This may be because the base value is equal to the speed that would be attained in a one second time trial, and therefore, represents the subjects' ability to produce short duration peak power. The exponent however, represents the entire set of time trials from 500m to 20 km and provides an indication of the subjects decay in speed from short to long distances. This value is therefore a better indicator of endurance performance specialization as it accounts for the subjects peak speed and their ability to maintain that speed.

It is suggested that the exponent value provided information about the subjects potential as an endurance predominant cyclist. Subjects who were able to maintain a large percentage of their peak speed over longer distances produced small negative exponent values. These subjects' may have had lower peak speeds than others, however their ability to maintain that speed provided them with a strong advantage in longer distance events. Those who produced highly negative exponents values had less natural ability to maintain their speed over long distances. These subjects may be more specialized to sprint performances, as they were not able to maintain a very high percentage of their peak speed over longer distances. The exponent value thus provides an overall inspection of the subjects cycling characteristics and may also be used as a tool to identify performance specialization.

The Logarithmic Model

The logarithmic model has been previously used to categorize runners as short, middle or long distance specialists. Bunc et al. (1991) found that runners produced slopes to the logarithmic model with a range of -0.9 to -2.1. Larger negative numbers were attributed to shorter distance specialists. In the present study, slope values ranged from -5.27 to -10.48. These values are much larger in magnitude than those found by Bunc et al. (1991) due to the higher speeds generated by cyclists compared to runners. Cyclists with the larger negative values were again more specialized towards short duration events. The mean slope of the log model for the entire group was -7.95 ± 1.52. The best sprint predominant cyclists produced values more negative than -9.00, while the best endurance predominant cyclists produced values less negative than -8.00. This model may be further studied in the future to determine if it can more specifically categorize a cyclists specification to a more narrow range of distances or even to a specific distance.

Conclusions

The 3-parameter nonlinear model and the 3-segmented long models of CS were found to be the best predictors of 40 km time trial performance and were the lowest estimates of CS. This result supports the previous findings of Gaesser et al. (1995) who found that the 3-parameter non-linear model estimated the lowest CP value. Furthermore, all of the CS models estimated speeds which were significantly greater than the speed at MLSS which has also been suggested (Housh et al. 1991; Poole et al. 1991; McLellan & Cheung, 1992).

This study found that the duration of the time trials used to calculate each model significantly effected the estimation of the CS parameter. Using both the 3-segmented model, and the distance vs. time model, CS estimations were found to be greater when the model was composed of shorter time trials. These results support the findings of Bishop et al. (1998) who found that the time frame of trials significantly affected the estimation of critical power.

The critical power and critical speed models were previously believed to be valid in the time frame between 1-10 minutes for predicting long duration performance. The present study provided evidence against this hypothesis. Using time trials within the time frame of 1-10 minutes, the CS model would only be capable of predicting a speed which would be sustainable by a cyclist for up to 35 minutes. The present study found that the speed vs. 1/time model could be used to predict the performance speed of a cyclist for any given distance. The model must however, be composed of time trials which are approximately 0.5, 0.25 of the desired distance and a third time trial that fits within the time domain of the appropriate model. Thus, the duration of time trials has a significant influence on predicted time to exhaustion for a criterion performance.

Key physiological variables were identified within the 3-segmented model which are suggested to be important for cycling performance in three time domains: short, medium and long duration. Peak power averaged over 1 second and the speed at $\dot{V}O_2$ max were associated with the short model which predicted speeds that were sustainable for approximately 3.7 minutes and is suggested to represent anaerobic-aerobic performance down to 100% $\dot{V}O_2$ max. The speed at MLSS and the speed at $\dot{V}O_2$ max were associated with the medium model which predicted speeds that were sustainable for approximately 35 minutes. This model may predict performance down to 90% $\dot{V}O_2$ max. The speed at MLSS, $\dot{V}O_2^{2/3}$ max and FFVT were associated with the long model, which predicted speeds that were sustainable for approximately 1.2 hours. This model represents long duration performance below 89% $\dot{V}O_2$ max.

These results do not support the theoretical concept that endurance performance can be estimated from CS modeling of short duration all-out tests of less than 15 min in duration, but demonstrate that the new 3-segmented long model may accurately predict 40 km time trial performance together with the 3-parameter nonlinear model.

Recommendations For Future Research

The present study has clearly demonstrated that CS cannot be maintained for a long time without fatigue. Future investigations may examine if a different model may be fit to similar data which does in fact predict a speed which is similar to the MLSS.

Because most laboratories perform their testing on cycle ergometers, modeling data is usually presented as power using the unit Watts. It would be beneficial to determine how power output corresponds to cycling speed either on the road or on rollers. This determination would allow for more detailed comparisons between studies and provide more practical information for training prescription based upon either modality.

The present study found many interesting results pertaining to the influence of certain physiological variables on cycling performance. There are however several other physiological variables which are involved in cycling performance which may have an equally important influence to those presently studied. Further research may look at which other variables are important along the progression from short to long distance cycling performance. Research may also focus on which variables contribute the performance for each type of cycling event including: track, mountain, road, and others. This type of analysis may lead to stronger, more specific results focused on a homogeneous subject pool.

Research using the power curve model may further explore the effect of training on the characteristics of the curve. This would be beneficial for determining the limits of potential improvement and also determine the range of events that an athlete performs successfully.

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Appendix A: Subject Consent Form

Human Performance Laboratory Consent Form

Project Title: Determination of the dominant physiological components of critical speed
Investigators: Perry D. Jacobson Under the supervision of Dr. D.J. Smith

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information mot included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The purpose of this study is to examine the relationship between critical speed and its underlying physiological components. Energy from both the aerobic and anaerobic systems are used during exercise at critical speed. This study will attempt to determine which physiological variables are most significant to such performance. The study will also examine the relationship between various models of critical speed.

Participation in this study will require one incremental cycling ride to exhaustion to determine maximal oxygen uptake ($\dot{V}O_2$ max) and speed at $\dot{V}O_2$max. A 30 second maximal effort Wingate test will initially be used to divide groups into predominantly aerobic and anaerobic athletes. You will then be required to perform 7 rides to exhaustion ranging in time from 30 seconds to 30 minutes. The order of these tests will be randomly assigned. Times from these rides will be used to determine models of critical speed. You will also be required to perform one fatiguing test of 55 maximal force contractions and one maximal contraction on a Cybex strength testing machine. An incremental cycling test will be performed which will involve the measurement of blood lactate. This test will involve up to 8 blood samples taken by the finger prick method. From this your maximum lactate steady state will be determined. To measure peak anaerobic power a 6 second maximal effort test will be performed. Anthropometric measurements will also be taken to evaluate muscle mass and body fat percentages. You will also be asked to describe your current training methods and volume of training.

There should be no long term detrimental effect to you by volunteering to be a subject for this study. Maximal effort testing may produce some dizziness, muscle soreness, or partial dehydration.

Knowledge gained by participation in this study will include, maximal oxygen uptake, maximal lactate steady state, predicted muscle fiber type, instantaneous anaerobic power and an estimation of critical speed. You will also receive a detailed analysis of how your scores compare to the two groups. This information will help to quantify your physical attributes which may be incorporated into your training program.

All information obtained will be kept in strict confidence and your name will not appear on any documents. A copy of this form will be given to you for your personal records.

Your participation is entirely voluntary and you may withdraw at any time. It is also a right of the investigators to terminate your involvement in the study if such a need arises.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. If you have any further questions concerning matters related to this research, please contact Dr. Walter Herzog, Associate Dean of Research, Faculty of Kinesiology, The University of Calgary 220-3438 or:
Perry Jacobson 220-2802

Participants' name	Signature	Date
Witness	Signature	Date
Investigator	Signature	Date

A copy of this consent form will be given to you. Please keep it for your records and future reference.

Appendix B: Subject information

Subject information Sheet

Equipment: Cycle testing will be done either on Kreitler rollers using your own bike or on an electronic cycle ergometer. Other equipment will include a Cybex II dynamometer and anthropometric equipment.

Maximal O_2 Consumption test ($\dot{V}O_2$max):

This test will involve a progressive ride on rollers to exhaustion. After a light warm up you will beginning the test at 25 km/h. Every two minutes you will be asked to increase your speed by 2 km/h until the point of ventilatory threshold. After this you will increase your speed by 1 km/h every minute until you have reached the point of fatigue or a plateau in $\dot{V}O_2$ is achieved.
Time: 30-40 minutes

Wingate test:

This test will be used to place you in either the endurance or sprint group. A 7 second test will be used to optimize the resistance for this test. You will then perform a 30 second full effort test at a set resistance. You will be given a rolling start and your goal is to achieve as many revolutions in 30 seconds as possible. This test will determine you anaerobic power and capacity.
Time: 15-20 minutes

Critical speed tests:

You will be required to perform 7 critical speed (CS) test. Each CS test timed maximal effort to a set distance. The object is to cover the set distance as quickly as possible with maximal effort. The distances you will cover are, 500, 1000, 1500, 2500, 4500, 10000, and 20000 m. The time frame for these tests should range between 30 seconds and 40 minutes.

The data from these 7 tests will be used to calculate your CS using several different mathematical models.

Critical Speed Criterion Test:

You will be asked to perform a 40km time trial. This will provide information about the validity of each CS model.

Muscle fiber type testing:

Seven measurements will be taken of your tested leg including lengths, girths and skin folds. These measurements will be used to calculate the fat free mass of the thigh.

On a Cybex II dynamometer, you will be required to perform two tests of the knee extensor muscles (quadriceps). In the first test you will perform 55 successive maximal contractions at a speed of $90^0 \cdot s^{-1}$. In the second test you will perform 4 maximal contractions at $280^0 \cdot s^{-1}$.

The results from these two tests will be used in an equation to determine the muscle fiber type distribution of your leg.
Time: 30 minutes

Maximal Lactate Steady State:

This test involves one high intensity ride (2 min) followed by 6 progressive 4 minute tests. The 4 minute tests will be at constant speeds ranging from 78-100% of your critical speed.

After the 2 km time trial you will be given a 5 minute rest. At the 4:30 mark of the rest period, a finger prick blood sample will be taken. Finger prick blood samples will also be taken after each 4 minute ride. The blood will be analyzed for lactic acid concentration. This provides an optimal speed at which you can ride without accumulating lactic acid.
Time 45 minutes

Anaerobic Power:

This test consists of 4 maximal 6 second all out sprint efforts on an electronic cycle ergometer. The first 3 will be used to determine your optimal resistance. The fourth test will be used to determine your peak instantaneous power.
Time: 30 minutes

Anthropometry:

Body fat percentage and lean muscle mass will be determined. This will be done by measuring height, weight, and various lengths girths and skin folds.
Time: 15 minutes

Appendix C: Project Time Frame.

The testing for this study was done between January and April of 1998. The testing required 13 testing days in 4 week blocks.

The first test performed was incremental determination of $\dot{V}O_2$ max.

The order of the critical speed, criterion test, Cybex and instantaneous power testing sessions were randomized, with up to two tests performed on one day.

The maximal lactate steady state test was performed after the determination of critical speed.

Table 12. Sequencing of testing sessions.

Study Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Test 1	A	A	CS	CS	CS	R	R	CS	CS	CS	CS	P	R	R	C	M	M
Test 2	V	V															

A- Anthropometry
C- Cybex
CS- critical speed and criterion test
M- maximal lactate steady state
P- maximal power and capacity
R- Rest
V- $\dot{V}O_2$ max

Appendix D: Raw Data

Table 13. Critical speed estimates (km·h^{-1}) of the 7 models for each subject individually.

Subject	Group	Distance vs. Time	1/time	Short	Medium	Long	2-parameter hyperbola	3-Parameter Hyperbola
1	1	37.1	40.1	47.0	37.2	37.2	37.2	37.2
2	1	34.6	37.3	43.6	35.5	34.2	34.4	34.2
3	1	33.5	37.0	40.3	35.3	31.6	32.7	31.8
4	1	34.9	38.4	42.6	36.4	33.1	34.1	33.4
5	1	33.8	36.2	41.0	33.7	34.1	34.0	34.0
6	1	35.3	38.6	43.6	36.7	33.9	33.3	34.0
7	1	33.8	37.3	40.6	35.4	31.0	34.6	32.5
8	1	33.1	35.5	40.7	33.3	32.2	32.6	32.4
9	2	30.2	32.6	35.8	30.2	28.2	29.5	28.6
10	2	33.8	35.7	39.5	35.0	33.2	33.6	33.3
11	2	35.3	37.8	40.9	35.9	34.0	34.6	34.1
12	2	39.2	41.6	44.3	39.7	38.5	38.8	38.4
13	2	34.6	36.5	40.3	34.6	34.2	34.3	34.2
14	2	36.4	38.3	40.9	36.9	36.0	36.1	35.9
15	2	30.2	31.0	34.1	31.0	28.9	29.9	29.7
16	2	29.9	33.5	38.6	31.7	28.6	29.4	28.7
17	2	37.1	39.0	40.9	38.3	35.6	36.4	35.8
18	2	34.6	36.3	39.4	34.2	34.9	34.9	34.9
19	2	35.6	38.7	41.9	37.0	33.8	34.8	33.9
20	2	32.4	35.4	40.6	32.5	31.4	31.8	31.4
21	2	34.2	36.7	39.4	35.2	32.6	33.4	32.7

Group 1 - Sprint Predominant
Group 2 - Endurance Predominant

Table 14. Results of the maximum lactate steady state, $\dot{V}O_2$ max and 40 km criterion ride.

Subject	Group	MLSS ($km \cdot h^{-1}$)	40km Speed ($km \cdot h^{-1}$)	% Type II	$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	$\dot{V}O_2$ speed ($km \cdot h^{-1}$)
1	1	33.2	35.0	51.5	57.1	44.0
2	1	31.4	32.4	49.9	48.1	40.0
3	1	31.0	33.3	43.1	62.0	41.0
4	1	33.2	34.7	57.8	47.7	43.0
5	1	30.9	33.2	46.5	53.9	41.0
6	1	31.8	33.8	59.0	58.9	43.0
7	1	30.9	33.9	36.5	58.3	42.0
8	1	30.7	31.4	55.1	56.8	41.0
9	2	28.2	29.9	41.4	53.3	36.0
10	2	31.0	33.6	36.1	64.0	40.0
11	2	31.8	35.2	33.1	70.2	41.0
12	2	35.7	38.5	42.5	72.1	45.0
13	2	31.3	33.2	29.8	63.0	41.0
14	2	32.9	35.6	48.6	63.3	42.0
15	2	27.4	28.0	31.1	57.6	35.0
16	2	27.8	29.1	31.1	64.1	39.0
17	2	34.1	35.3	37.0	73.8	42.0
18	2	31.4	33.2	31.3	58.2	40.0
19	2	32.4	34.1	43.8	50.9	42.0
20	2	30.0	30.8	44.5	55.8	40.0
21	2	32.2	34.2	43.7	66.9	41.0

Group 1 - Sprint Predominant
Group 2 - Endurance Predominant

Table 15. Individual results from peak power testing.

Subject	Group	Instantaneous Power (W)	1 second Power (W)	Relative Instantaneous Power ($W \cdot kg^{-1}$)	Relative 1 second Power ($W \cdot kg^{-1}$)
1	1	2772.1	1704.1	32.0	19.7
2	1	2647.4	1511.2	29.7	16.9
3	1	2115.1	1292.0	30.0	18.3
4	1	3146.6	1921.1	38.1	23.3
5	1	2845.2	1540.3	34.1	18.5
6	1	2127.9	1224.1	30.7	17.7
7	1	2043.5	1211.5	26.0	15.4
8	1	2396.1	1277.0	29.6	15.8
9	2	1817.7	1060.3	26.3	15.3
10	2	2513.8	1481.0	31.5	18.6
11	2	2055.0	1164.2	32.8	18.6
12	2	2182.9	1290.4	31.9	18.8
13	2	2509.7	1305.4	32.6	16.9
14	2	2128.7	1230.2	27.1	15.7
15	2	1932.1	1053.0	30.2	16.5
16	2	1520.0	869.8	27.2	15.6
17	2	1747.0	970.0	27.6	15.4
18	2	1981.1	1128.5	28.5	16.2
19	2	2043.0	1143.4	25.6	14.3
20	2	2364.4	1405.0	32.5	19.3
21	2	1950.0	1200.0	27.3	16.8

Group 1 - Sprint Predominant
Group 2 - Endurance Predominant

Table 16. Individual modeling results from the power curve and logarithmic models.

Subject	Group	Log	Base	Exponent
1	1	-9.78	87.46	-0.1186
2	1	-9.80	91.99	-0.1362
3	1	-8.91	79.38	-0.1144
4	1	-10.48	91.095	-0.1294
5	1	-9.062	87.265	-0.131
6	1	-8.55	80.69	-0.1117
7	1	-9.59	84.86	-0.123
8	1	-9.07	85.343	-0.1303
9	2	-7.57	69.33	-0.1126
10	2	-6.72	74.69	-0.1089
11	2	-7.26	71.27	-0.0952
12	2	-6.67	66.19	-0.0712
13	2	-7.89	74.55	-0.1063
14	2	-6.51	71.4	-0.0931
15	2	-5.27	63.83	-0.1046
16	2	-8.67	66.64	-0.1027
17	2	-5.37	67.77	-0.00825
18	2	-5.82	56.9	-0.0672
19	2	-7.61	71.2	-0.0921
20	2	-9.09	69.25	-0.1007
21	2	-7.23	68.72	-0.0937

Group 1 - Sprint Predominant
Group 2 - Endurance Predominant

Table 17. Individual results from the anthropometric measurements measured.

Subject	Group	Weight (kg)	% Fat	F:M	FFVT (mL)
1	1	86.6	15.5	328	10398
2	1	71.5	13.1	291	8111
3	1	69.2	13.3	290	8065
4	1	79.8	10.0	175	9998
5	1	62.7	10.5	213	7783
6	1	68.5	9.4	190	8726
7	1	77.1	12.8	267	9215
8	1	78.6	10.5	214	9122
9	2	89.3	24.0	541	10781
10	2	55.9	10.8	198	5973
11	2	63.2	12.9	293	7068
12	2	70.6	14.6	331	8048
13	2	69.5	11.1	214	11259
14	2	79.8	15.2	327	9277
15	2	82.5	17.4	342	10663
16	2	72.8	10.6	213	9441
17	2	83.5	17.7	386	9601
18	2	69.3	12.0	243	8542
19	2	78.5	14.8	311	8322
20	2	81	18.3	387	8621
21	2	64	14.6	302	8043

Group 1 - Sprint Predominant
Group 2 - Endurance Predominant

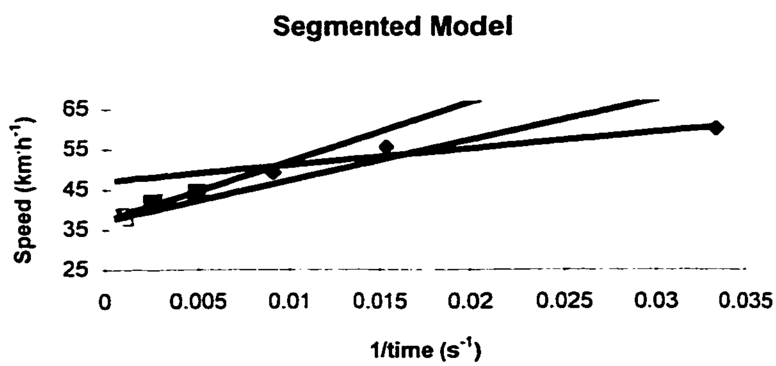
Appendix E: Individual Subject data sheets

Subject # 1

Distance (m)	(km)	Time (s)	Speed (km.h-1)
500	0.5	30	60.00
1000	1	65	55.38
1500	1.5	110	49.09
2500	2.5	204	44.12
4500	4.5	388	41.75
10000	10	940	38.30
20000	20	1907	37.76

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	44.0	
short	46.97	0.876
medium	37.19	0.948
Long	37.23	1
2-Parameter	37.18	0.99
3-Parameter	37.2	0.99
40 KM	35.02	
Speed at MLSS	33.2	

1



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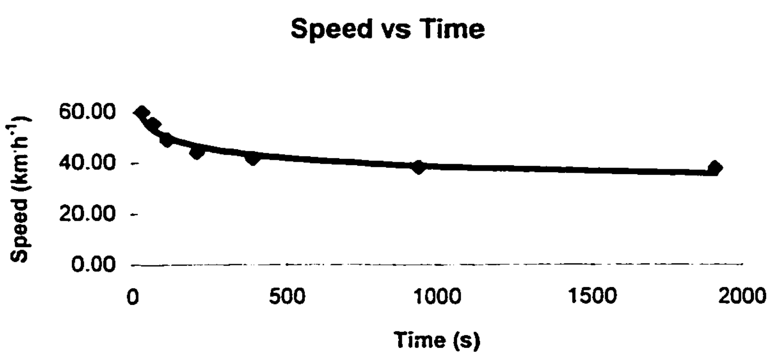


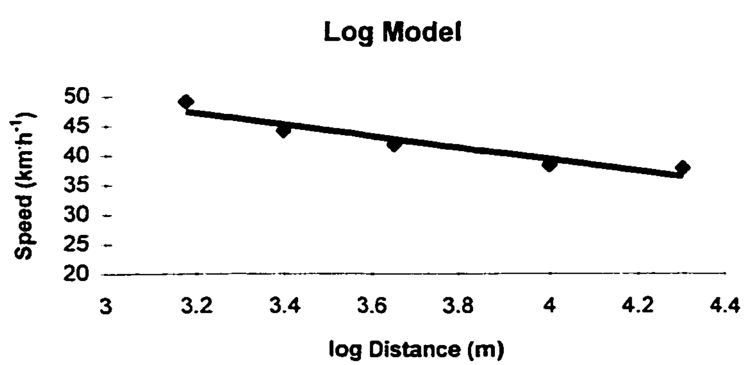
Power Curve

Base	87.46
Exponent	-0.12

Non-Linear CS

2-Parameter	37.18
3-Parameter	37.2

3



Logarithmic Model

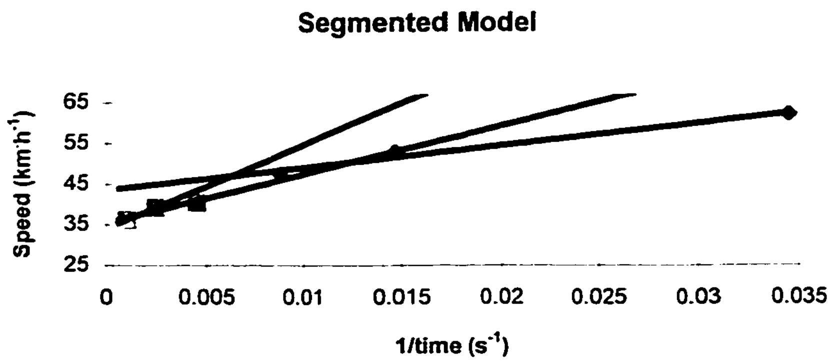
Log	-9.78

Subject #2

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	29	62.07
1000	1	68	52.94
1500	1.5	114	47.37
2500	2.5	222	40.54
4500	4.5	413	39.23
10000	10	994	36.22
20000	20	2048	35.16

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	40.0	
short	43.62	0.974
medium	35.51	0.894
Long	34.16	1
2-Parameter	34.35	0.99
3-Parameter	34.18	0.99
40 KM	32.40	
Speed at MLSS	31.4	

1



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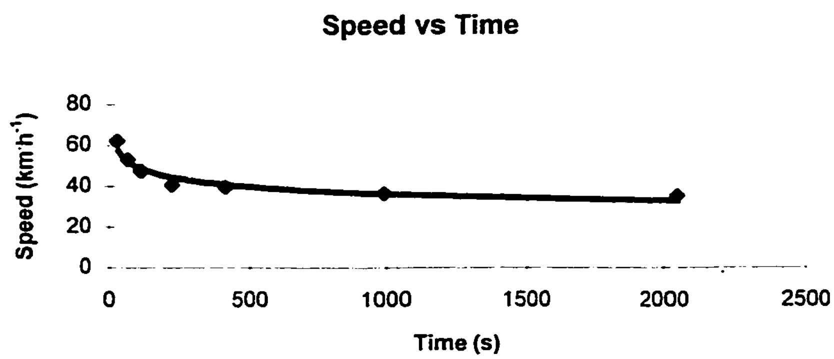


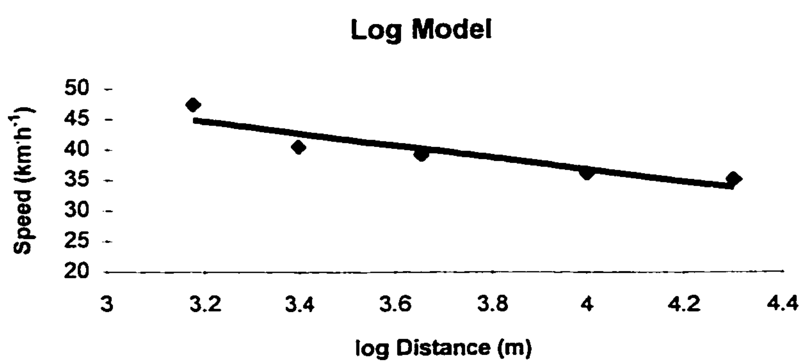
Power Curve

Base	91.99
Exponent	-0.14

Non-Linear CS

2-Parameter	34.35
3-Parameter	34.18

3



Logarithmic Model

Log	-9.8

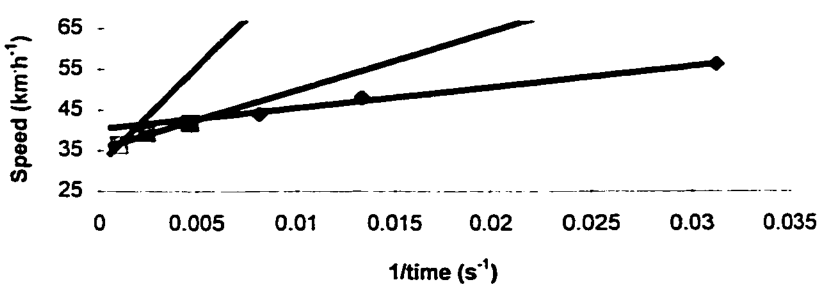
Subject #3

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	32	56.25
1000	1	75	48.00
1500	1.5	123	43.90
2500	2.5	215	41.86
4500	4.5	411	39.42
10000	10	987	36.47
20000	20	2126	33.87

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	41.0	
short	40.33	0.987
medium	35.34	0.968
Long	31.61	1
2-Parameter	32.72	0.95
3-Parameter	31.84	0.97
40 KM	33.32	
Speed at MLSS	31.0	

1

Segmented Model



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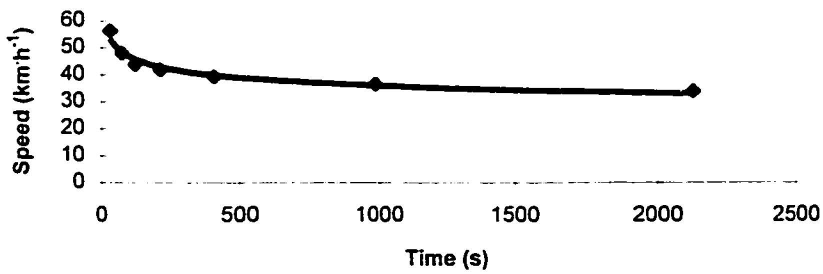
Speed vs Time



Power Curve

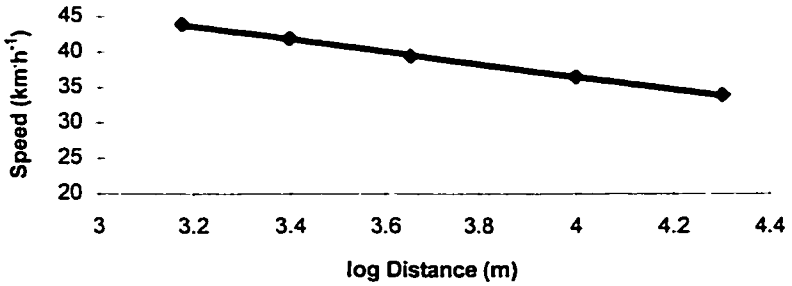
Base	79.38
Exponent	-0.11

Non-Linear CS

2-Parameter	32.72
3-Parameter	31.84

3

Log Model



Logarithmic Model

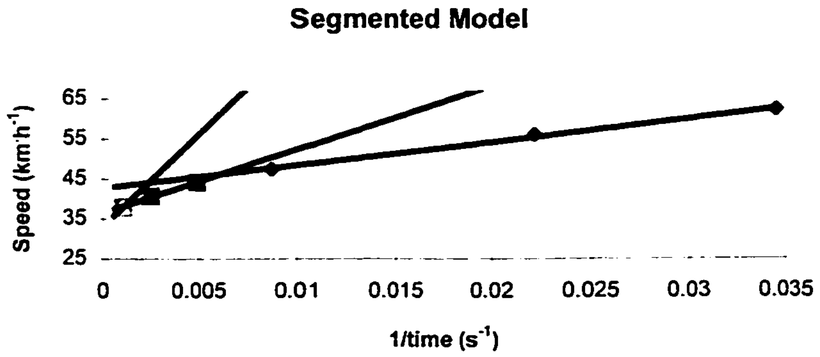
Log	-8.91

Subject #4

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	29	62.07
700	0.7	45	56.00
1500	1.5	114	47.37
2500	2.5	204	44.12
4500	4.5	398	40.70
10000	10	949	37.93
20000	20	2037	35.35

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	43.0	
short	42.64	0.995
medium	36.43	0.994
Long	33.09	1
2-Parameter	34.14	0.96
3-Parameter	33.44	1
40 KM	34.75	
Speed at MLSS	33.2	

1



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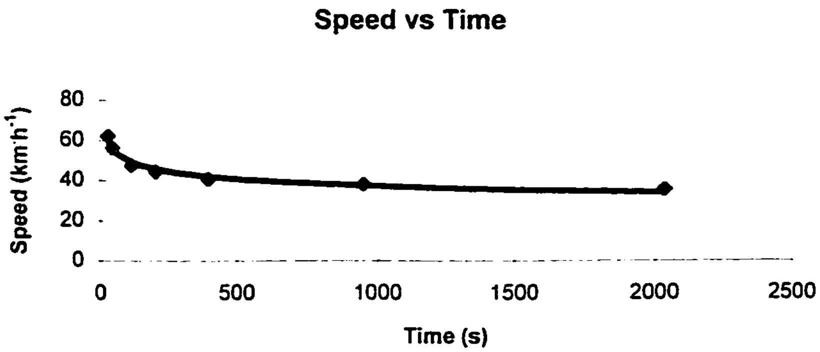


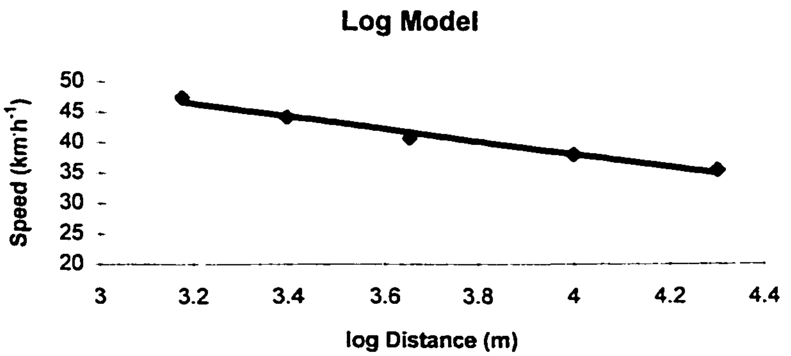
Power Curve

Base	91.1
Exponent	-0.13

Non-Linear CS

2-Parameter	34.14
3-Parameter	33.44

3



Logarithmic Model

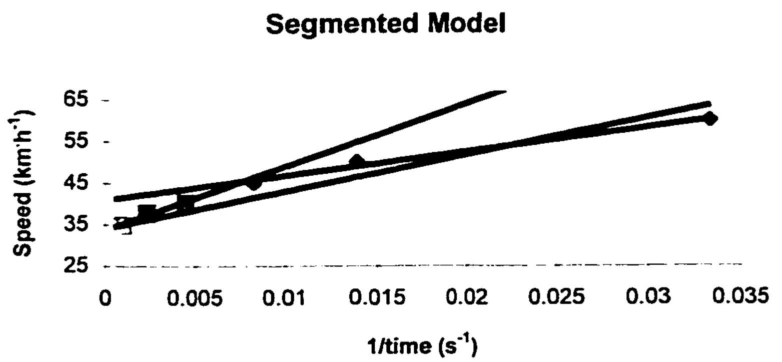
Log	-10.5

Subject #5

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	30	60.00
1000	1	72	50.00
1500	1.5	120	45.00
2500	2.5	223	40.36
4500	4.5	429	37.76
10000	10	1031	34.92
20000	20	2088	34.48

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	41.0	
short	40.97	0.986
medium	33.74	0.976
Long	34.06	1
2-Parameter	33.99	0.99
3-Parameter	34.0	0.99
40 KM	33.21	
Speed at MLSS	30.9	

1



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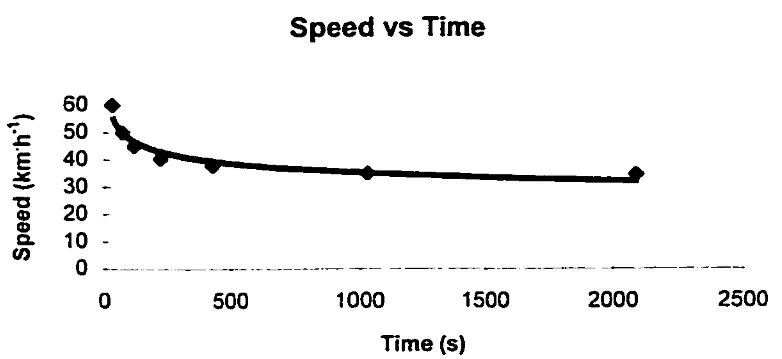


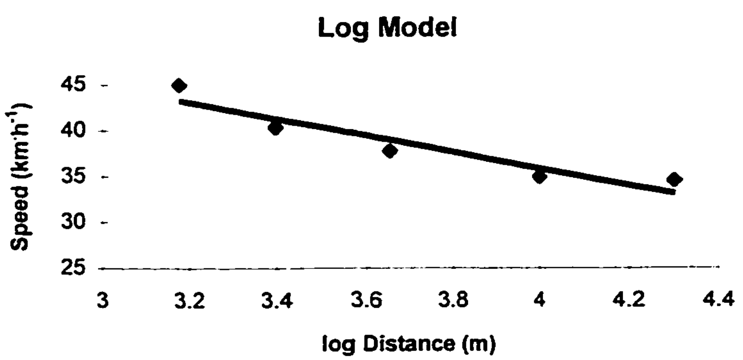
Power Curve

Base	87.27
Exponent	-0.13

Non-Linear CS

2-Parameter	33.99
3-Parameter	34

3



Logarithmic Model

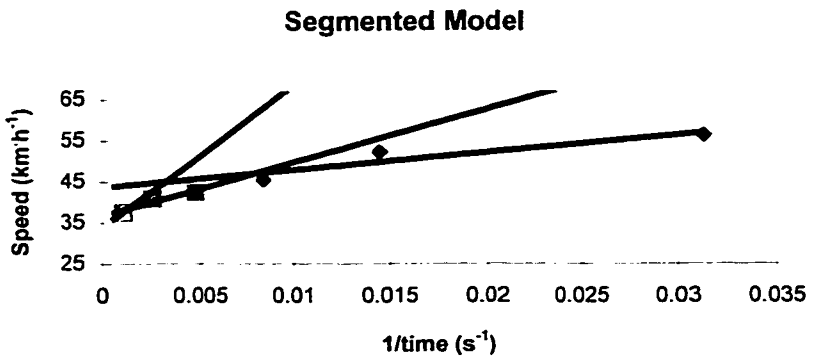
Log	-9.06

Subject #6

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	32	56.25
1000	1	69	52.17
1500	1.5	119	45.38
2500	2.5	212	42.45
4500	4.5	396	40.91
10000	10	960	37.50
20000	20	2022	35.61

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	43.0	
short	43.57	0.844
medium	36.7	0.898
Long	33.9	1
2-Parameter	33.25	0.97
3-Parameter	33.98	0.99
40 KM	33.83	
Speed at MLSS	31.8	

1



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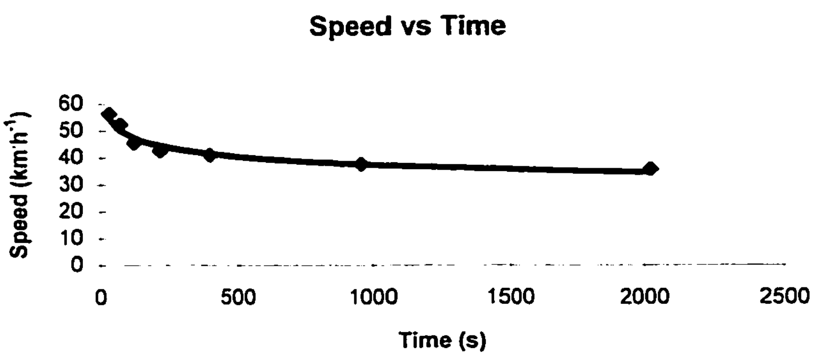


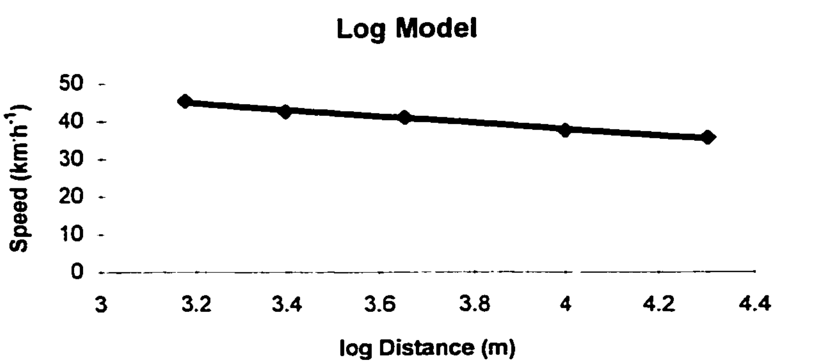
Power Curve

Base	80.69
Exponent	-0.11

Non-Linear CS

2-Parameter	33.25
3-Parameter	33.98

3



Logarithmic Model

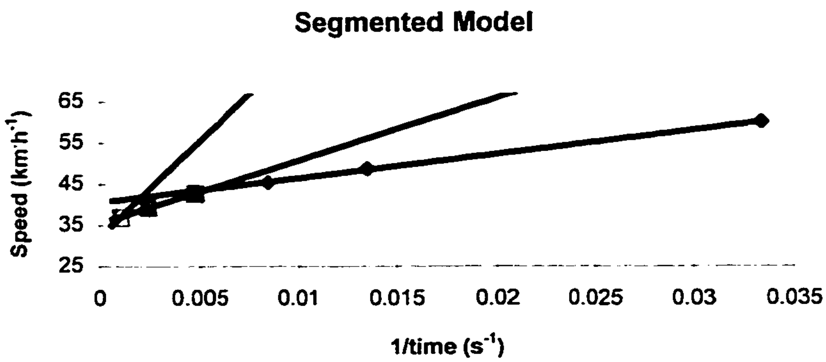
Log	-8.55

Subject #7

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	30	60.00
1000	1	74	48.65
1500	1.5	119	45.38
2500	2.5	211	42.65
4500	4.5	412	39.32
10000	10	974	36.96
20000	20	2093	34.40

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	42.0	
short	40.61	1
medium	35.4	0.998
Long	31.01	1
2-Parameter	34.56	0.95
3-Parameter	32.53	0.99
40 KM	33.93	
Speed at MLSS	30.9	

1



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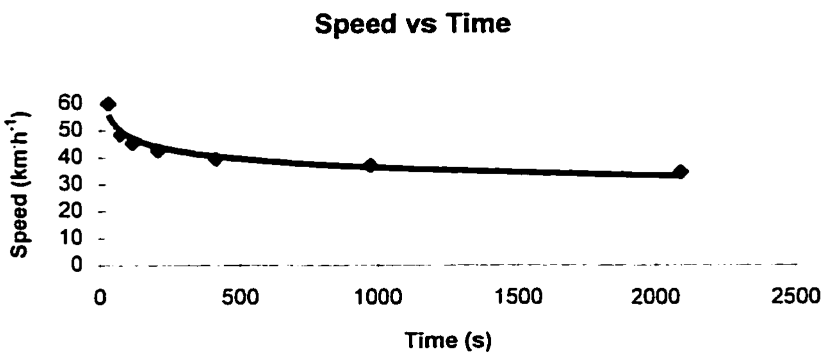


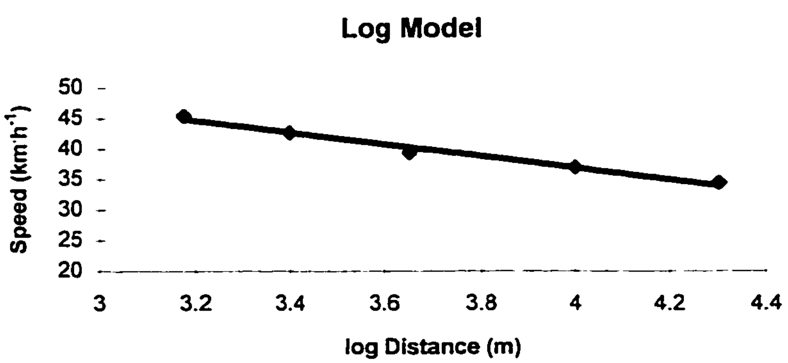
Power Curve

Base	84.86
Exponent	-0.12

Non-Linear CS

2-Parameter	34.56
3-Parameter	32.53

3



Logarithmic Model

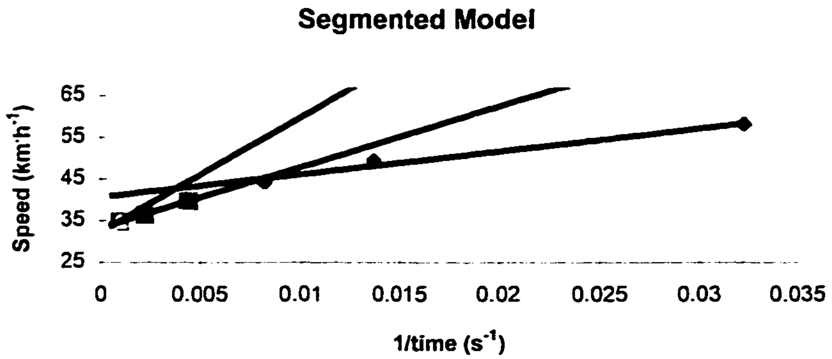
Log	-9.59

Subject # 8

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	31	58.06
1000	1	73	49.32
1500	1.5	122	44.26
2500	2.5	226	39.82
4500	4.5	445	36.40
10000	10	1033	34.85
20000	20	2152	33.46

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	41.0	
short	40.66	0.978
medium	33.33	0.996
Long	32.17	1
2-Parameter	32.64	0.98
3-Parameter	32.39	0.99
40 KM	31.40	
Speed at MLSS	30.7	

1



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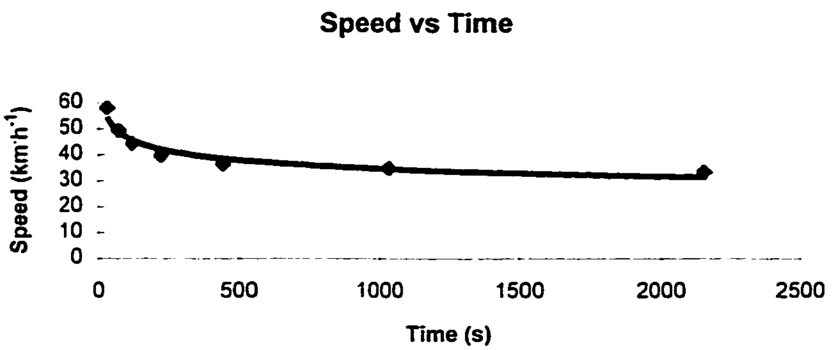


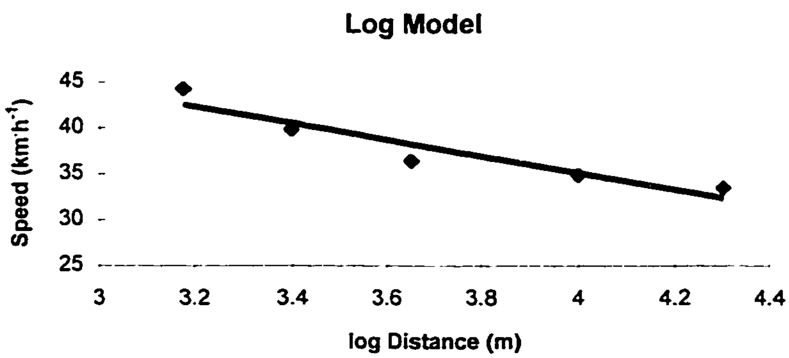
Power Curve

Base	85.34
Exponent	-0.13

Non-Linear CS

2-Parameter	32.64
3-Parameter	32.39

3



Logarithmic Model

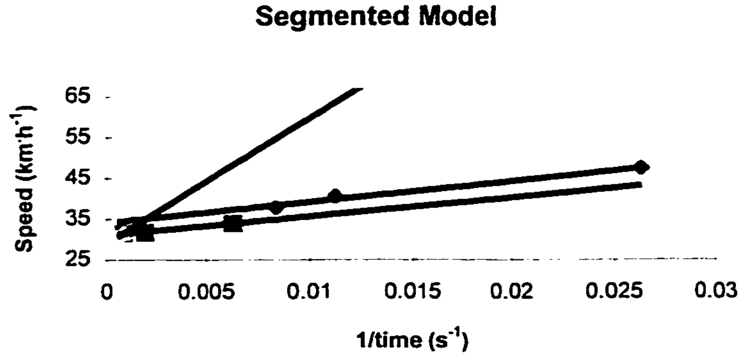
Log	-9.07

Subject # 9

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	38	47.37
1000	1	89	40.45
1250	1.25	119	37.82
1500	1.5	159	33.96
4500	4.5	510	31.76
10000	10	1141	31.55
15000	15	1765	30.59

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	36.0	
short	35.8	0.906
medium	30.19	0.985
Long	28.21	1
2-Parameter	29.5	0.93
3-Parameter	28.63	0.98
40 KM	29.87	
Speed at MLSS	28.2	

1



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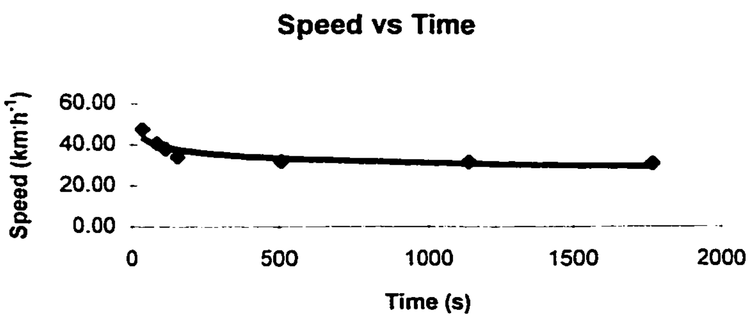


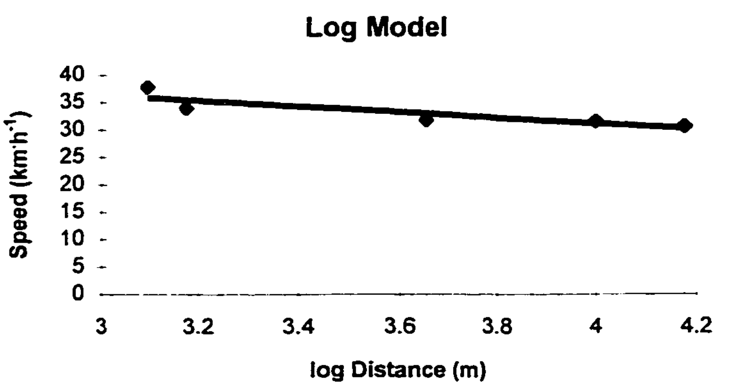
Power Curve

Base	69.33
Exponent	-0.11

Non-Linear CS

2-Parameter	29.5
3-Parameter	28.63

3



Logarithmic Model

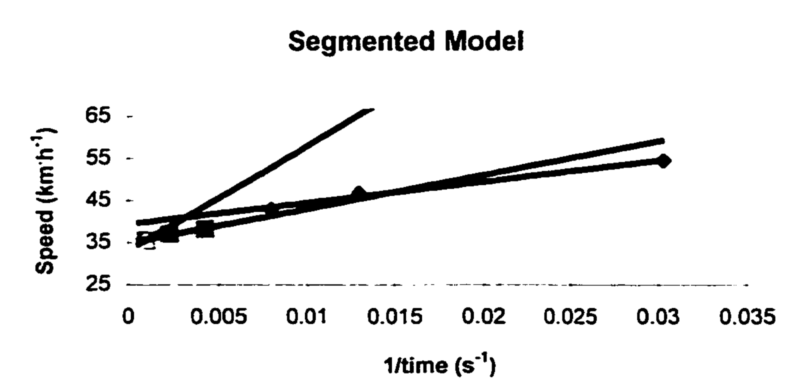
Log	-7.57

Subject #10

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	33	54.55
1000	1	77	46.75
1500	1.5	126	42.86
2500	2.5	235	38.30
4500	4.5	436	37.16
10000	10	1011	35.61
20000	20	2097	34.33

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	40.0	
short	39.45	0.987
medium	35.0	0.96
Long	33.15	1
2-Parameter	33.58	0.97
3-Parameter	33.34	0.99
40 KM	33.57	
Speed at MLSS	31.0	

1



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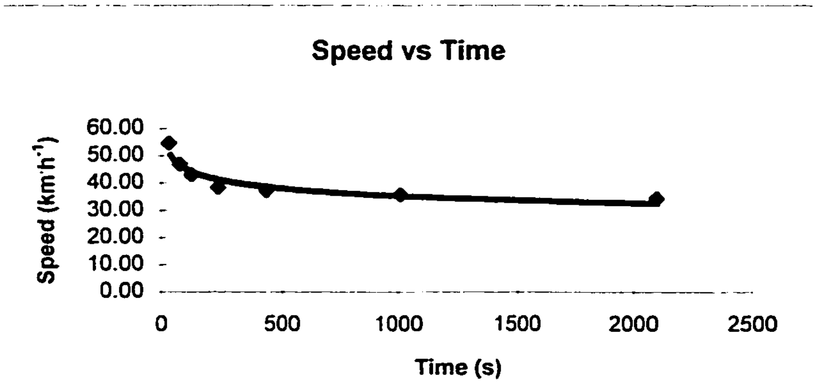


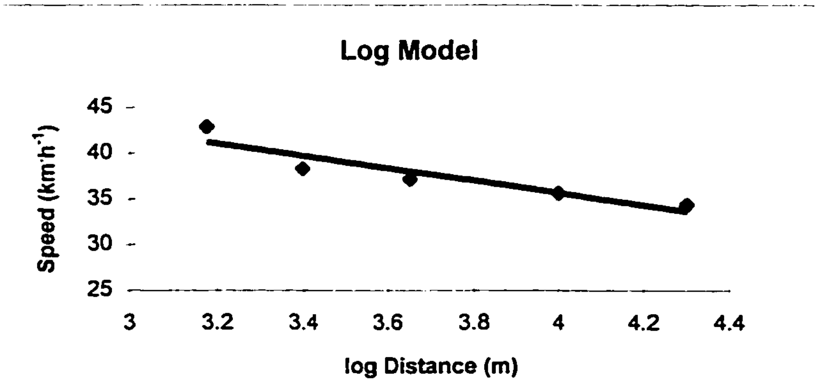
Power Curve

Base	74.69
Expontent	-0.11

Non-Linear CS

2-Parameter	33.58
3-Parameter	33.34

3



Logarithmic Model

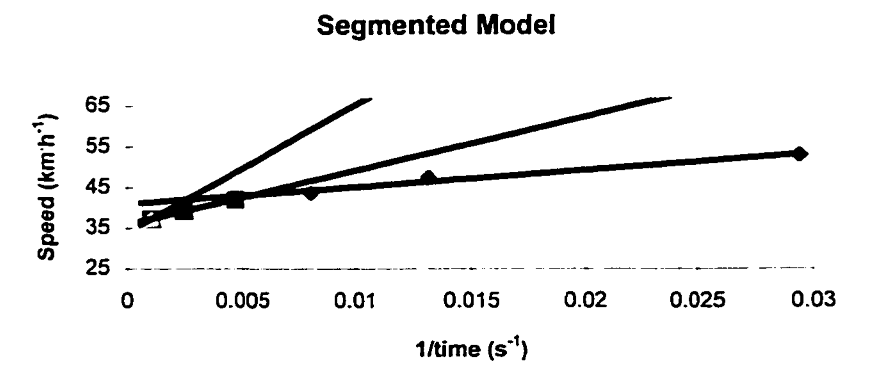
Log	-6.72

Subject # 11

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	34	52.94
1000	1	76	47.37
1500	1.5	124	43.55
2500	2.5	214	42.06
4500	4.5	413	39.23
10000	10	967	37.23
20000	20	2026	35.54

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	41.0	
short	40.93	0.966
medium	35.93	0.999
Long	33.99	1
2-Parameter	34.63	0.96
3-Parameter	34.09	0.99
40 KM	35.16	
Speed at MLSS	31.8	

1



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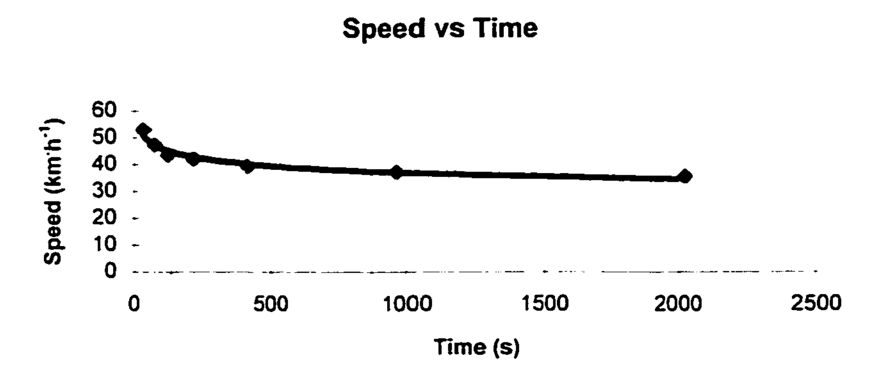


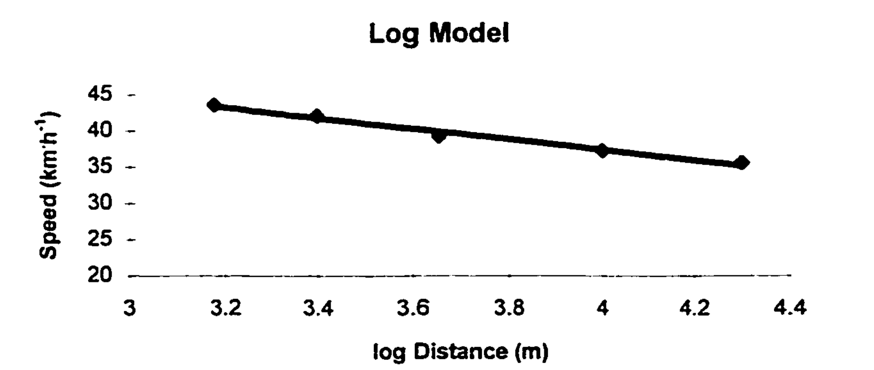
Power Curve

Base	71.27
Exponent	-0.1

Non-Linear CS

2-Parameter	34.63
3-Parameter	34.09

3



Logarithmic Model

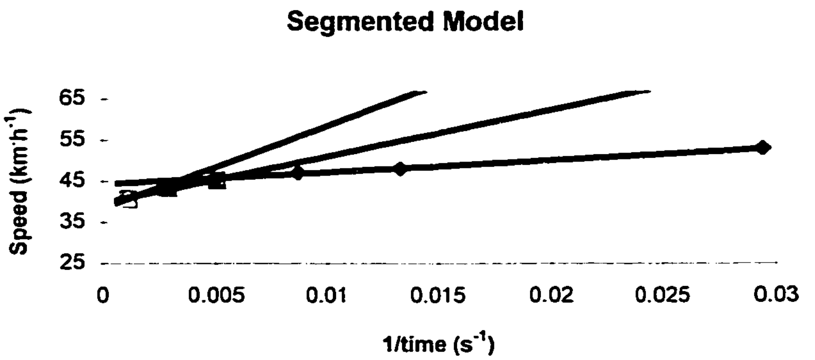
Log	-7.26

Subject # 12

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	34	52.94
1000	1	75	48.00
1500	1.5	115	46.96
2500	2.5	199	45.23
4220	4.22	350	43.41
10000	10	883	40.77
20000	20	1818	39.60

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	45.0	
short	44.26	0.997
Medium	39.73	0.971
Long	38.5	1
2-Parameter	38.83	0.98
3-Parameter	38.38	1
40 KM	38.49	
Speed at MLSS	35.7	

1



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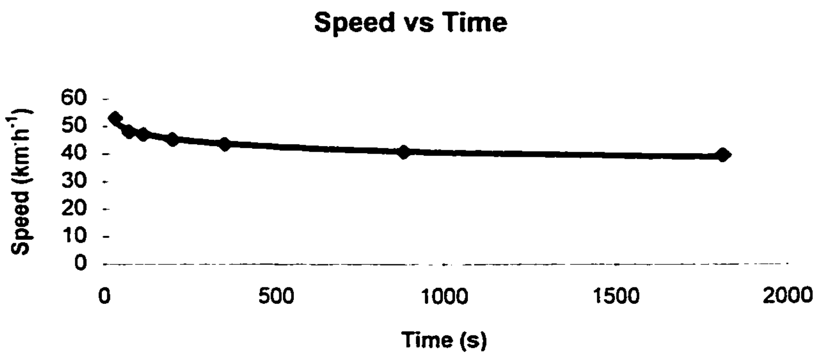


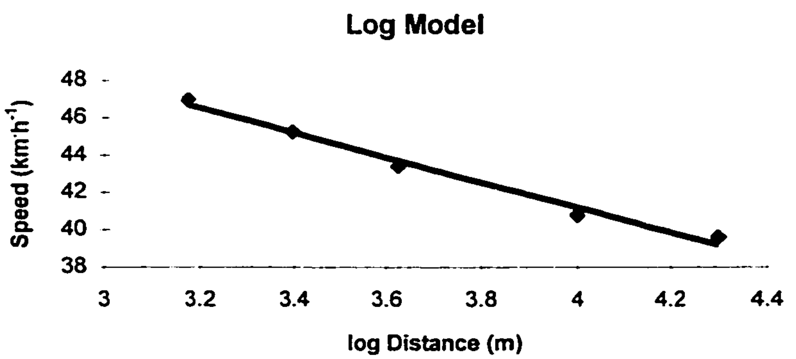
Power Curve

Base	66.19
Exponent	-0.07

Non-Linear CS

2-Parameter	38.83
3-Parameter	38.38

3



Logarithmic Model

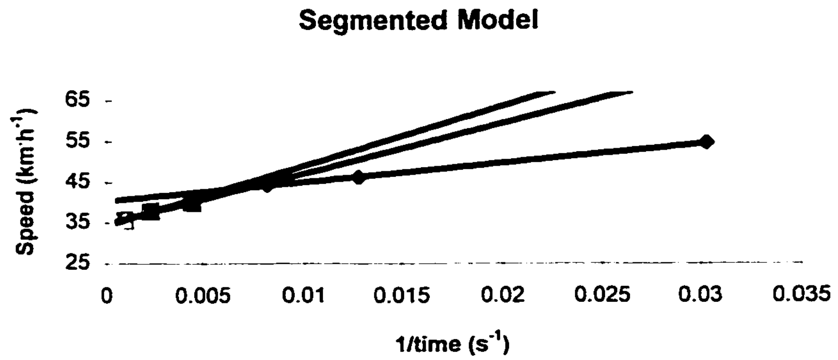
Log	-6.67

Subject # 13

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	33	54.55
1000	1	78	46.15
1500	1.5	122	44.26
2500	2.5	225	40.00
4500	4.5	428	37.85
10000	10	1010	35.64
20000	20	2063	34.90

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	41.0	
short	40.29	0.999
medium	34.62	0.982
Long	34.18	1
2-Parameter	34.27	0.99
3-Parameter	34.16	1
40 KM	33.20	
Speed at MLSS	31.3	

1



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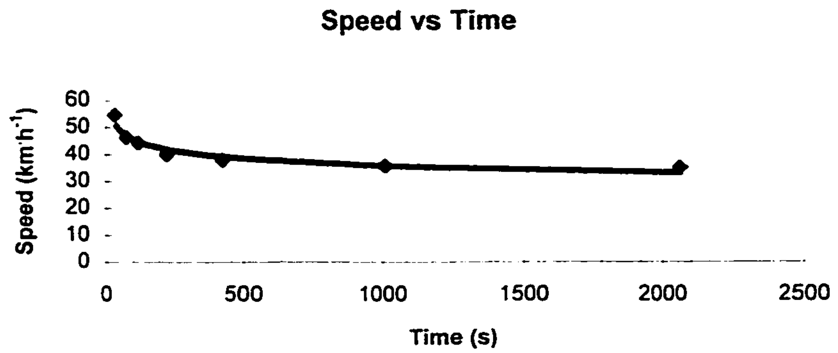


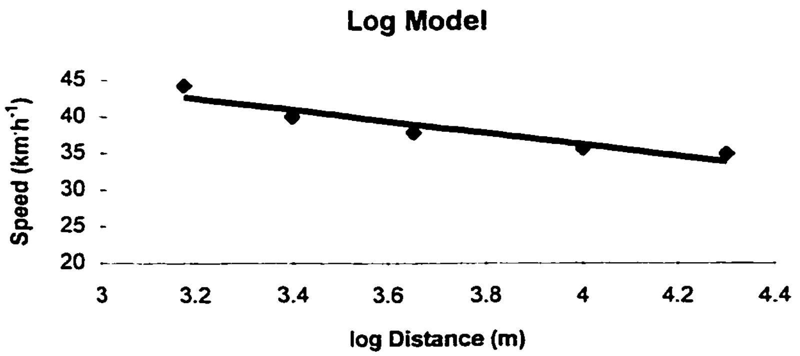
Power Curve

Base	74.55
Exponent	-0.11

Non-Linear CS

2-Parameter	34.27
3-Parameter	34.16

3



Logarithmic Model

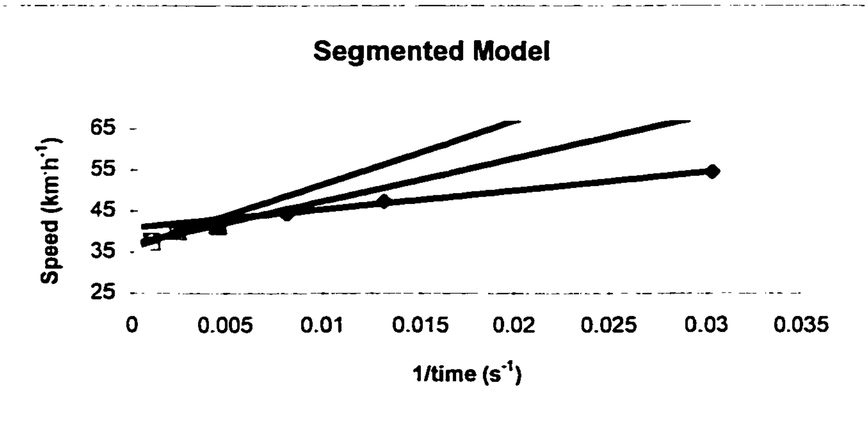
Log	-7.89

Subject # 14

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	33	54.55
1000	1	76	47.37
1500	1.5	122	44.26
2500	2.5	217	41.47
4500	4.5	403	40.20
10000	10	957	37.62
20000	20	1957	36.79

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	42.0	
short	40.92	0.99
medium	36.93	0.913
Long	36.0	1
2-Parameter	36.12	0.99
3-Parameter	35.9	0.93
40 KM	35.57	
Speed at MLSS	32.9	

1



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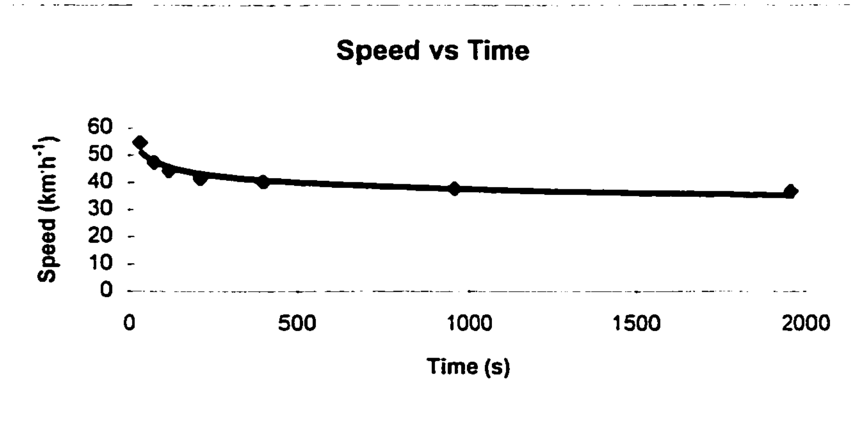


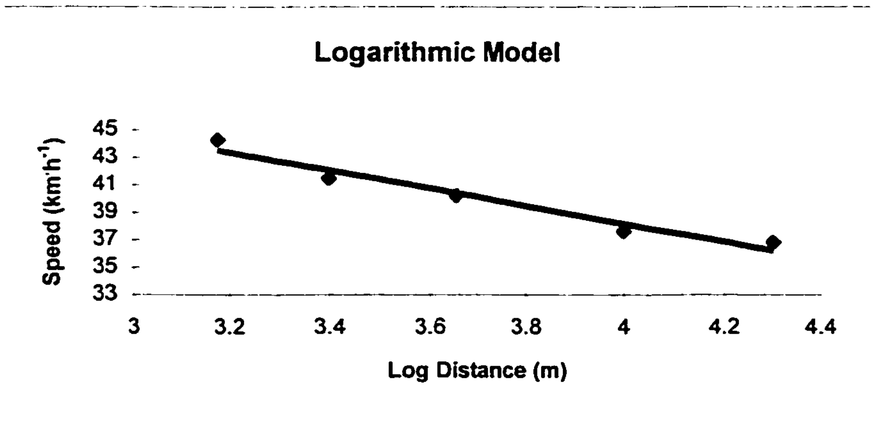
Power Curve

Base	71.4
Exponent	-0.09

Non-Linear CS

2-Parameter	36.12
3-Parameter	35.9

3



Logarithmic Model

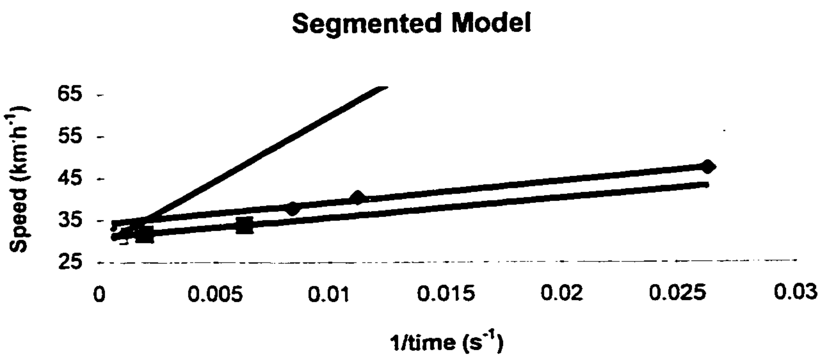
Log	-6.51

Subject # 15

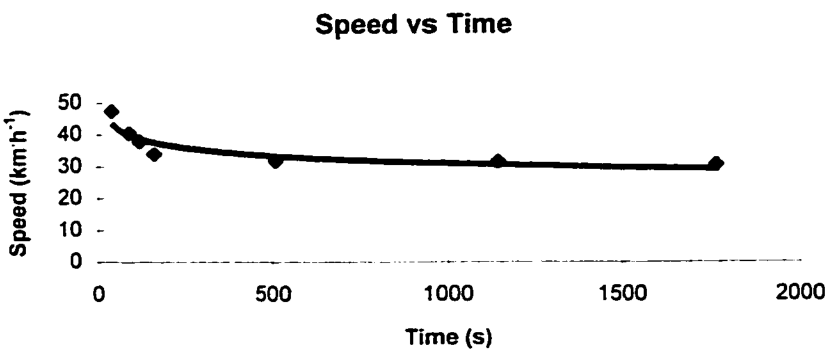
Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	38	47.37
1000	1	89	40.45
1250	1.25	119	37.82
1500	1.5	159	33.96
4500	4.5	510	31.76
10000	10	1141	31.55
15000	15	1765	30.59

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	35.0	
short	34.09	0.985
medium	31.02	0.988
Long	28.85	1
2-Parameter	29.89	0.91
3-Parameter	29.71	1
40 KM	28.00	
Speed at MLSS	27.4	

1



2



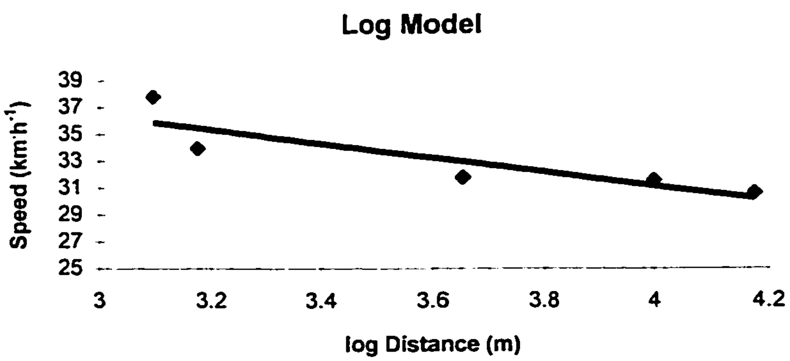
Power Curve

Base	63.83
Exponent	-0.1

Non-Linear CS

2-Parameter	29.89
3-Parameter	29.71

3



Logarithmic Model

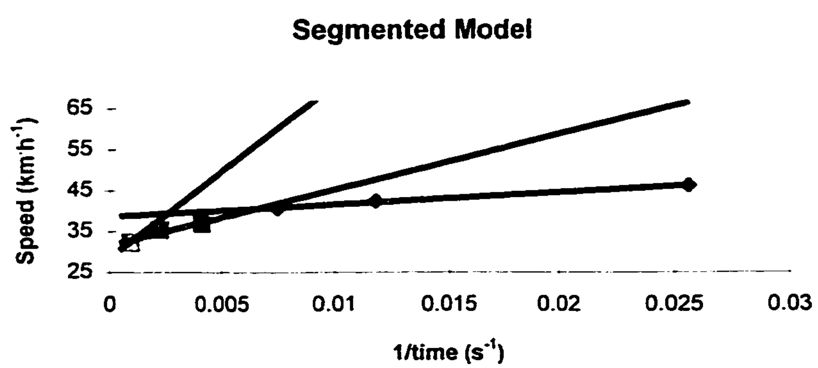
Log	-5.27

Subject #16

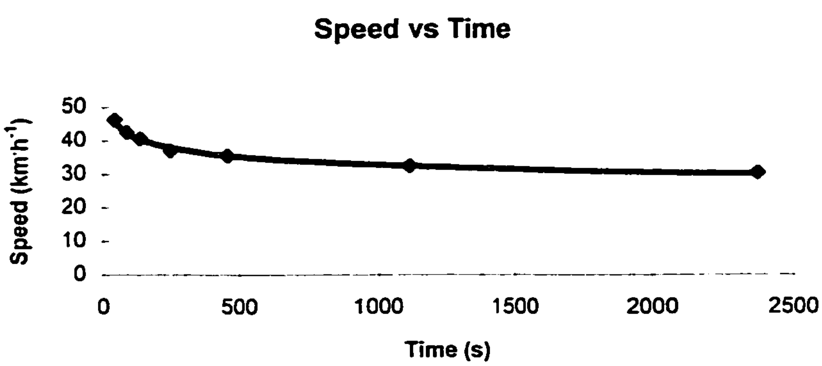
Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	39	46.15
1000	1	85	42.35
1500	1.5	133	40.60
2500	2.5	244	36.89
4500	4.5	457	35.45
10000	10	1112	32.37
20000	20	2371	30.37

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	39.0	
short	38.57	0.992
medium	31.65	0.902
Long	28.59	1
2-Parameter	29.38	0.96
3-Parameter	28.73	0.98
40 KM	29.10	
Speed at MLSS	27.8	

1



2



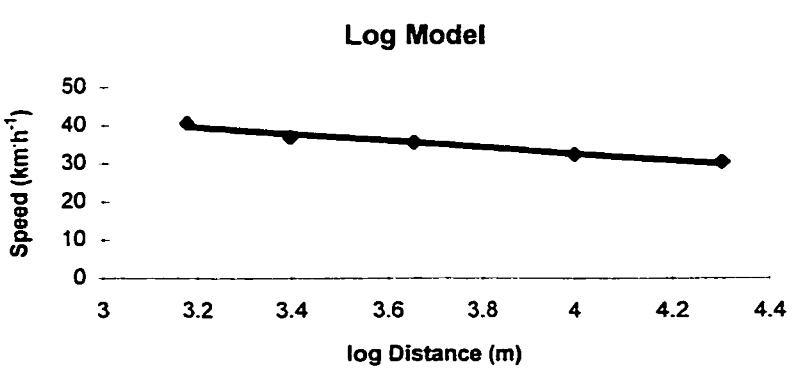
Power Curve

Base	66.64
Exponent	-0.1

Non-Linear CS

2-Parameter	29.38
3-Parameter	28.73

3



Logarithmic Model

Log	-8.67

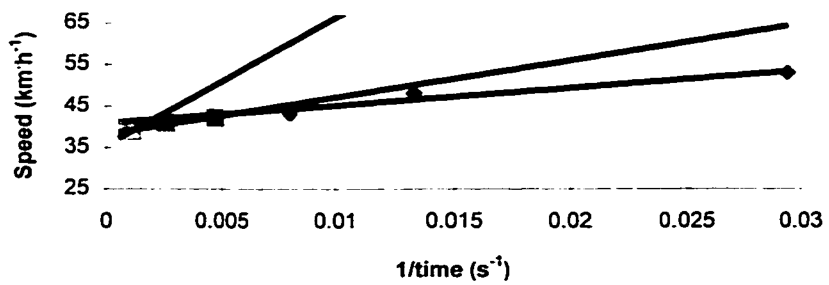
Subject #17

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	34	52.94
1000	1	75	48.00
1500	1.5	125	43.20
2500	2.5	213	42.25
4500	4.5	395	41.01
10000	10	924	38.96
20000	20	1934	37.23

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	42.0	
short	40.93	0.927
medium	38.29	0.937
Long	35.64	1
2-Parameter	36.36	0.95
3-Parameter	35.79	0.99
40 KM	35.33	
Speed at MLSS	34.1	

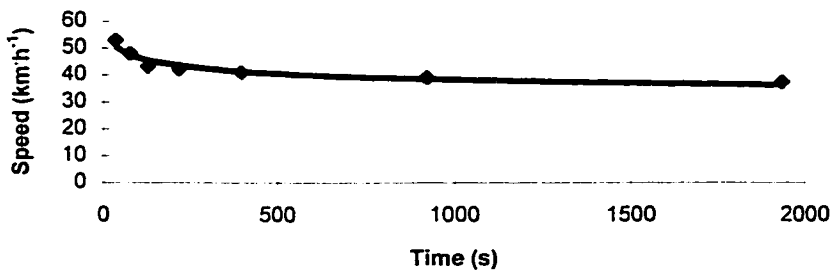
1

Segmented Model



2

Speed vs Time



Power Curve

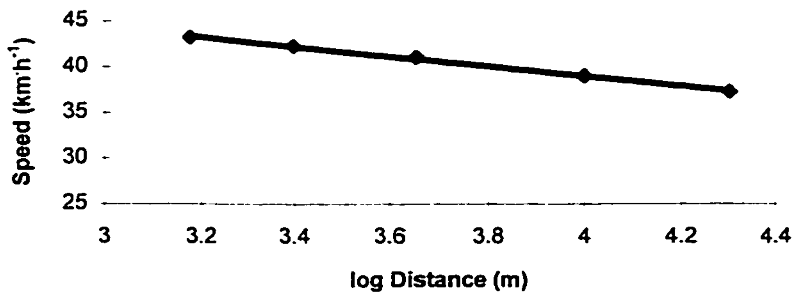
Base	67.77
Exponent	-0.01

Non-Linear CS

2-Parameter	36.36
3-Parameter	35.79

3

Log Model



Logarithmic Model

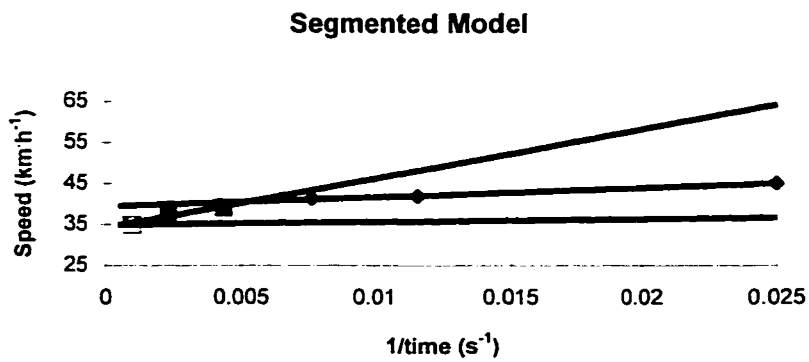
Log	-5.37

Subject #18

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	40	45.00
1000	1	86	41.86
1500	1.5	131	41.22
2500	2.5	230	39.13
4500	4.5	430	37.67
10000	10	1030	34.95
20000	20	2062	34.92

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	40.0	
short	39.42	0.996
medium	34.2	0.92
Long	34.88	1
2-Parameter	34.89	0.95
3-Parameter	34.89	0.99
40 KM	33.22	
Speed at MLSS	31.4	

1



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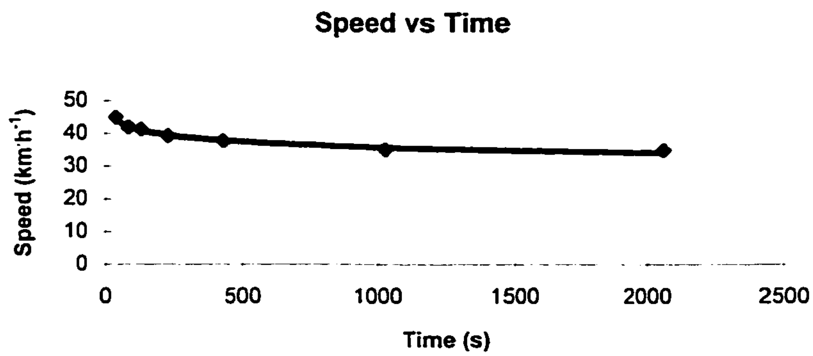


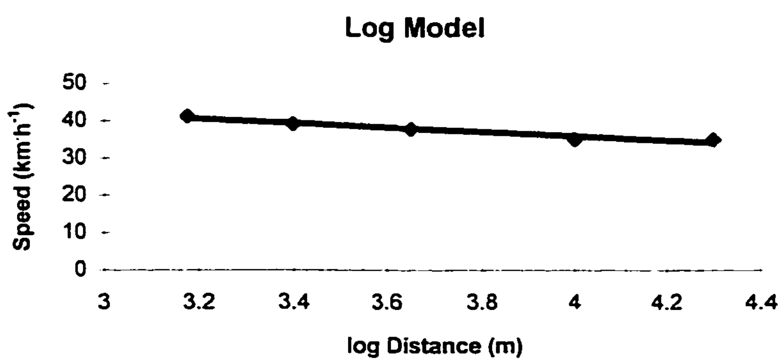
Power Curve

Base	56.9
Exponent	-0.07

Non-Linear CS

2-Parameter	34.89
3-Parameter	34.89

3



Logarithmic Model

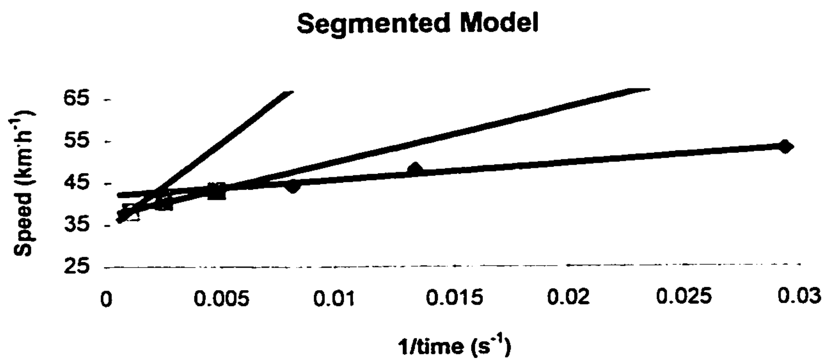
Log	-5.82

Subject #19

Distance (m)	(km)	Time (s)	Speed (km·h^{-1})
500	0.5	34	52.94
1000	1	75	48.00
1500	1.5	122	44.26
2500	2.5	209	43.06
4500	4.5	399	40.60
10000	10	943	38.18
20000	20	2008	35.86

Model	Speed (km·h^{-1})	r^2
Speed at VO_2 max	42.0	
short	41.87	0.957
medium	37.02	0.985
Long	33.8	1
2-Parameter	34.75	0.93
3-Parameter	33.87	0.99
40 KM	34.06	
Speed at MLSS	32.4	

1



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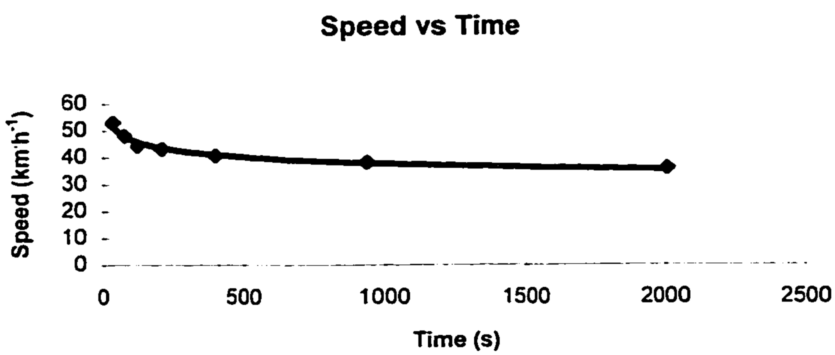


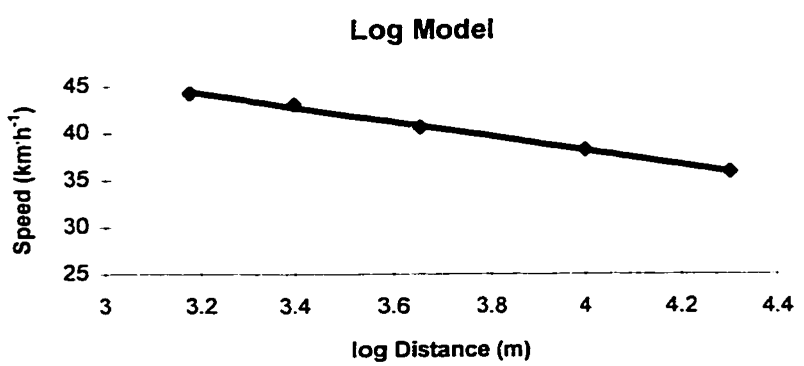
Power Curve

Base	71.2
Exponent	-0.09

Non-Linear CS

2-Parameter	34.75
3-Parameter	33.87

3



Logarithmic Model

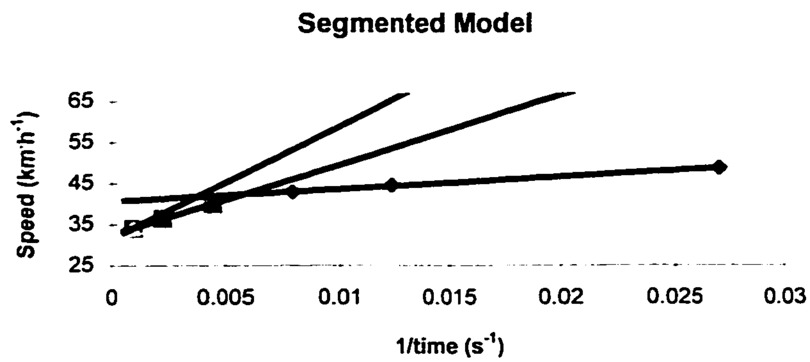
Log	-7.61

Subject #20

Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	37	48.65
1000	1	81	44.44
1500	1.5	126	42.86
2500	2.5	225	40.00
4500	4.5	444	36.49
10000	10	1058	34.03
20000	20	2203	32.68

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	40.0	
short	40.6	0.998
medium	32.51	0.998
Long	31.44	1
2-Parameter	31.82	0.98
3-Parameter	31.4	0.99
40 KM	30.77	
Speed at MLSS	30.0	

1



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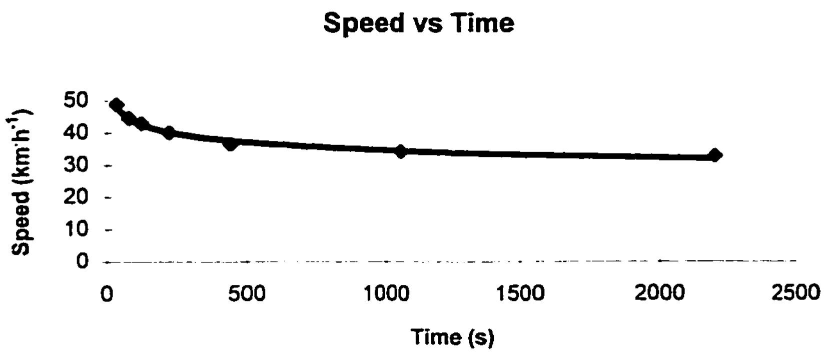


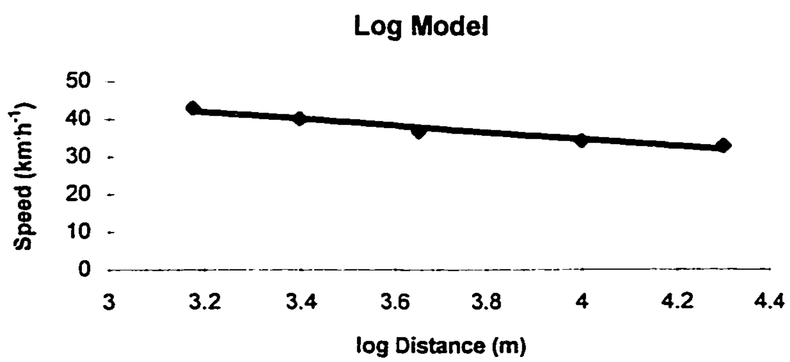
Power Curve

Base	69.25
Exponent	-0.1

Non-Linear CS

2-Parameter	31.82
3-Parameter	31.4

3



Logarithmic Model

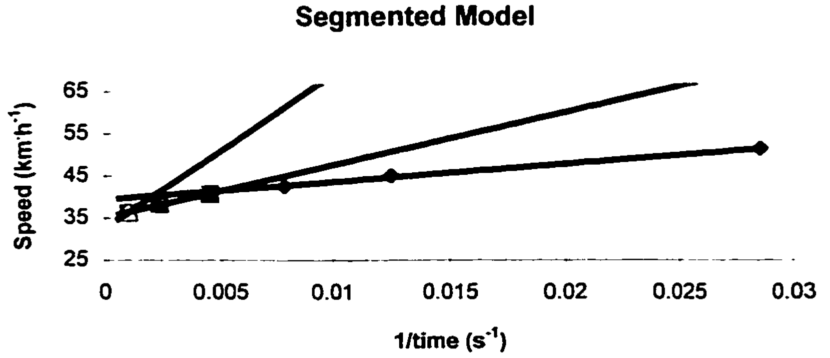
Log	-9.09

Subject # 21

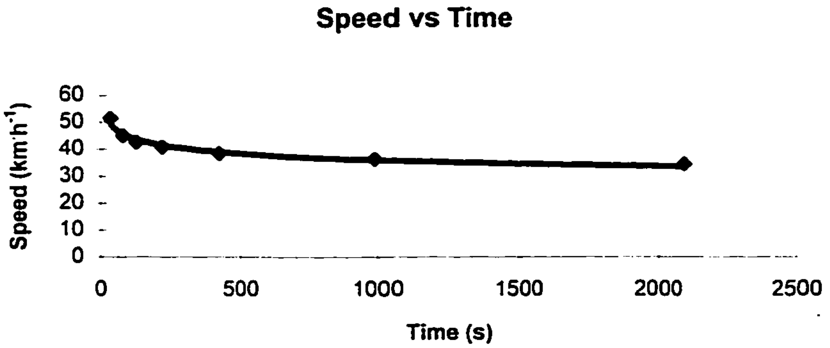
Distance (m)	(km)	Time (s)	Speed ($km \cdot h^{-1}$)
500	0.5	35	51.43
1000	1	80	45.00
1500	1.5	127	42.52
2500	2.5	221	40.72
4500	4.5	423	38.30
10000	10	992	36.29
20000	20	2096	34.35

Model	Speed ($km \cdot h^{-1}$)	r^2
Speed at VO_2 max	41.0	
short	39.42	0.997
medium	35.15	0.994
Long	32.61	1
2-Parameter	33.4	0.95
3-Parameter	32.72	0.99
40 KM	34.20	
Speed at MLSS	32.2	

1



2



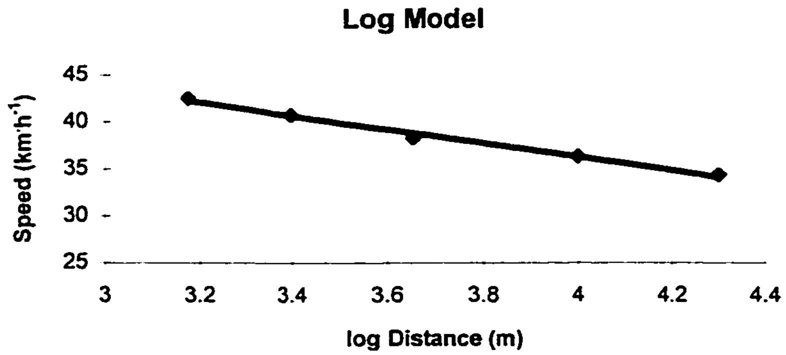
Power Curve

Base	68.72
Exponent	-0.09

Non-Linear CS

2-Parameter	33.4
3-Parameter	32.72

3

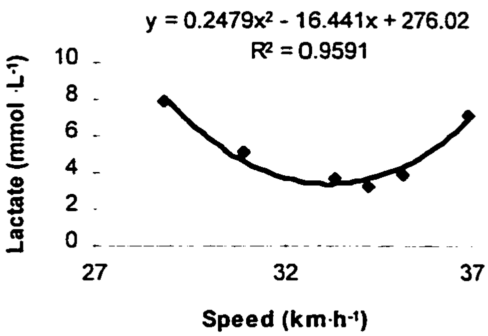


Logarithmic Model

Log	-7.23

Appendix F: Maximal Lactate Steady State Curves

By Subject Number.



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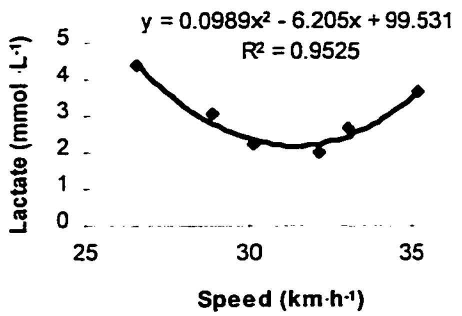
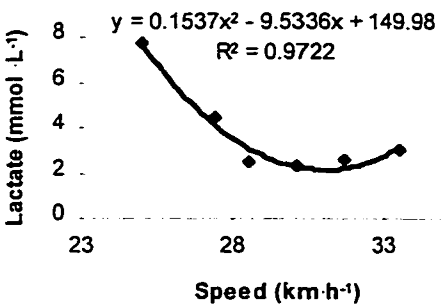


2.



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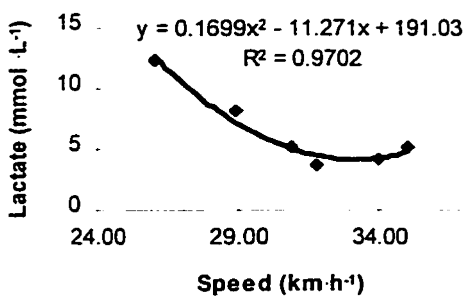

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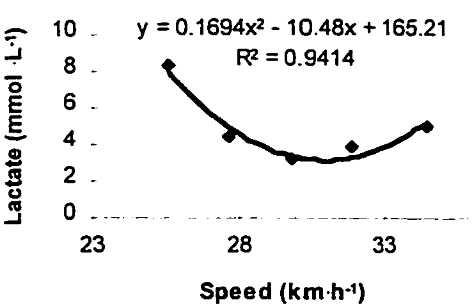
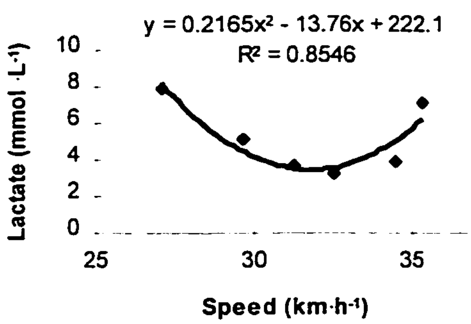
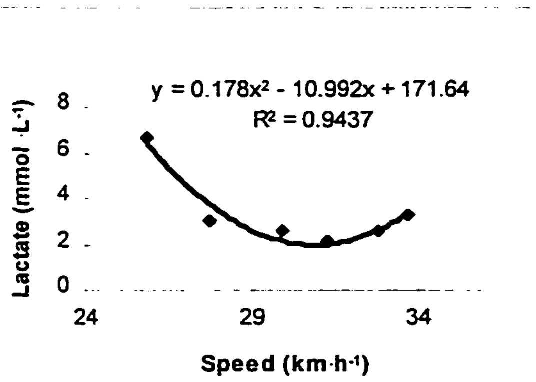


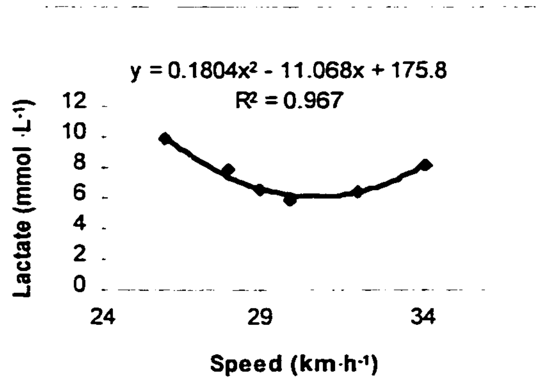
5.



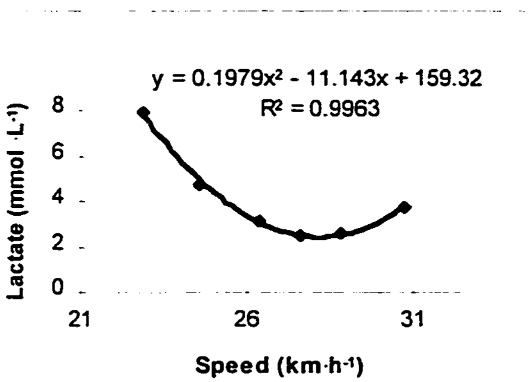
6.


y = 0.178x² - 10.992x + 171.64
R² = 0.9437
Lactate (mmol ·L⁻¹)
8
6
4
2
0
24
29
34
Speed (km·h⁻¹)

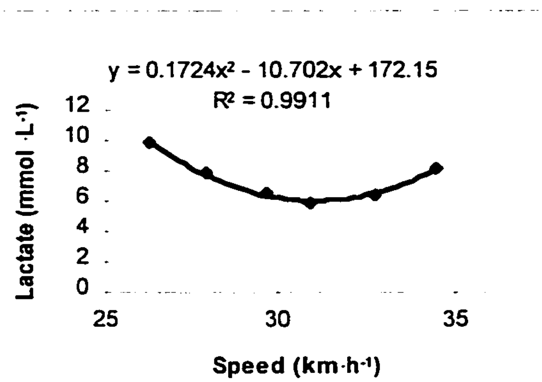
7.


y = 0.1804x² - 11.068x + 175.8
R² = 0.967
Lactate (mmol ·L⁻¹)
12
10
8
6
4
2
0
24
29
34
Speed (km·h⁻¹)

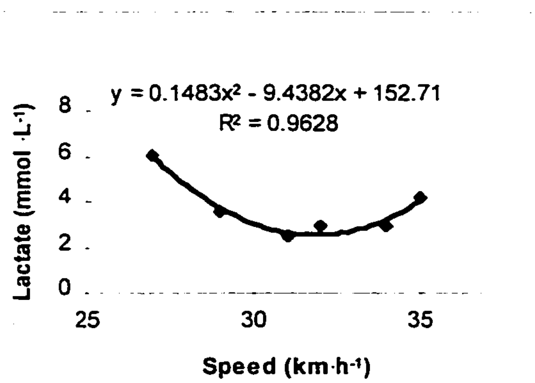
8.


y = 0.1979x² - 11.143x + 159.32
R² = 0.9963
Lactate (mmol ·L⁻¹)
8
6
4
2
0
21
26
31
Speed (km·h⁻¹)

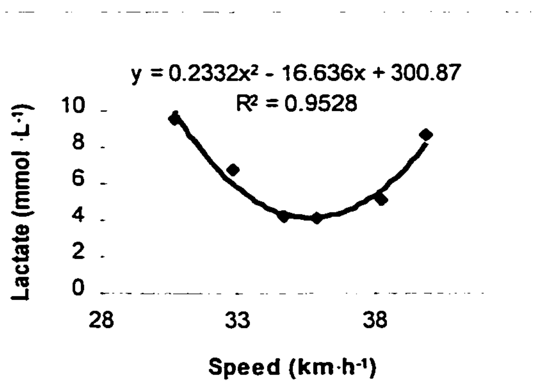
9.


y = 0.1724x² - 10.702x + 172.15
R² = 0.9911
Lactate (mmol ·L⁻¹)
12
10
8
6
4
2
0
25
30
35
Speed (km·h⁻¹)

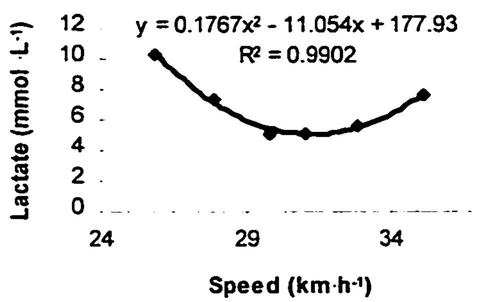
10.


y = 0.1483x² - 9.4382x + 152.71
R² = 0.9628
Lactate (mmol ·L⁻¹)
8
6
4
2
0
25
30
35
Speed (km·h⁻¹)

11.


y = 0.2332x² - 16.636x + 300.87
R² = 0.9528
Lactate (mmol ·L⁻¹)
10
8
6
4
2
0
28
33
38
Speed (km·h⁻¹)

12



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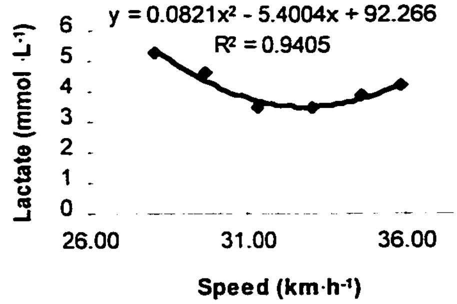

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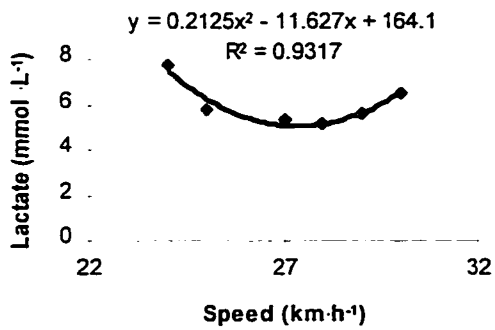

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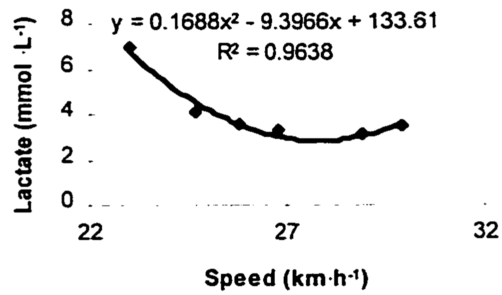

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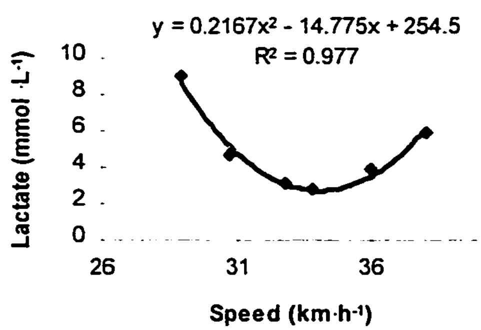

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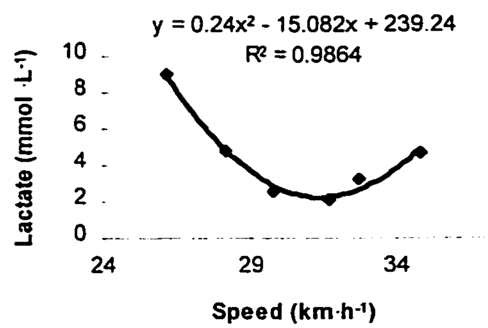
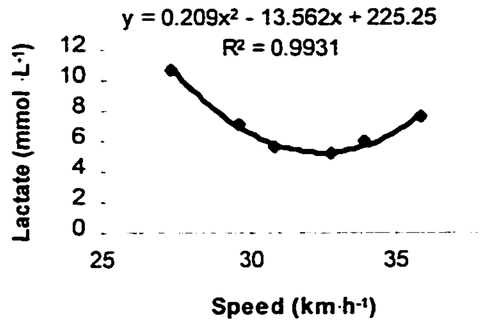
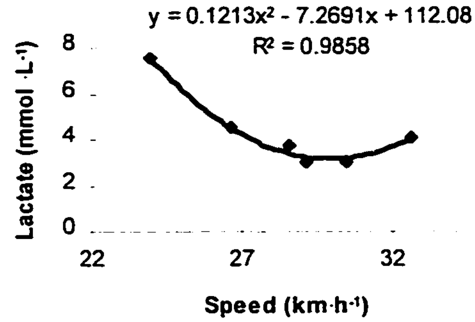


18.



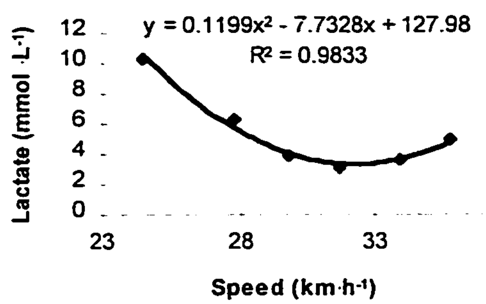
y = 0.209x² - 13.562x + 225.25
R² = 0.9931
Lactate (mmol ·L⁻¹)
12
10
8
6
4
2
0
25
30
35
Speed (km·h⁻¹)

19.



y = 0.1213x² - 7.2691x + 112.08
R² = 0.9858
Lactate (mmol ·L⁻¹)
8
6
4
2
0
22
27
32
Speed (km·h⁻¹)

20.



y = 0.1199x² - 7.7328x + 127.98
R² = 0.9833
Lactate (mmol ·L⁻¹)
12
10
8
6
4
2
0
23
28
33
Speed (km·h⁻¹)

21.

Appendix G: Statistical Analysis

Analysis of variance with repeated measures

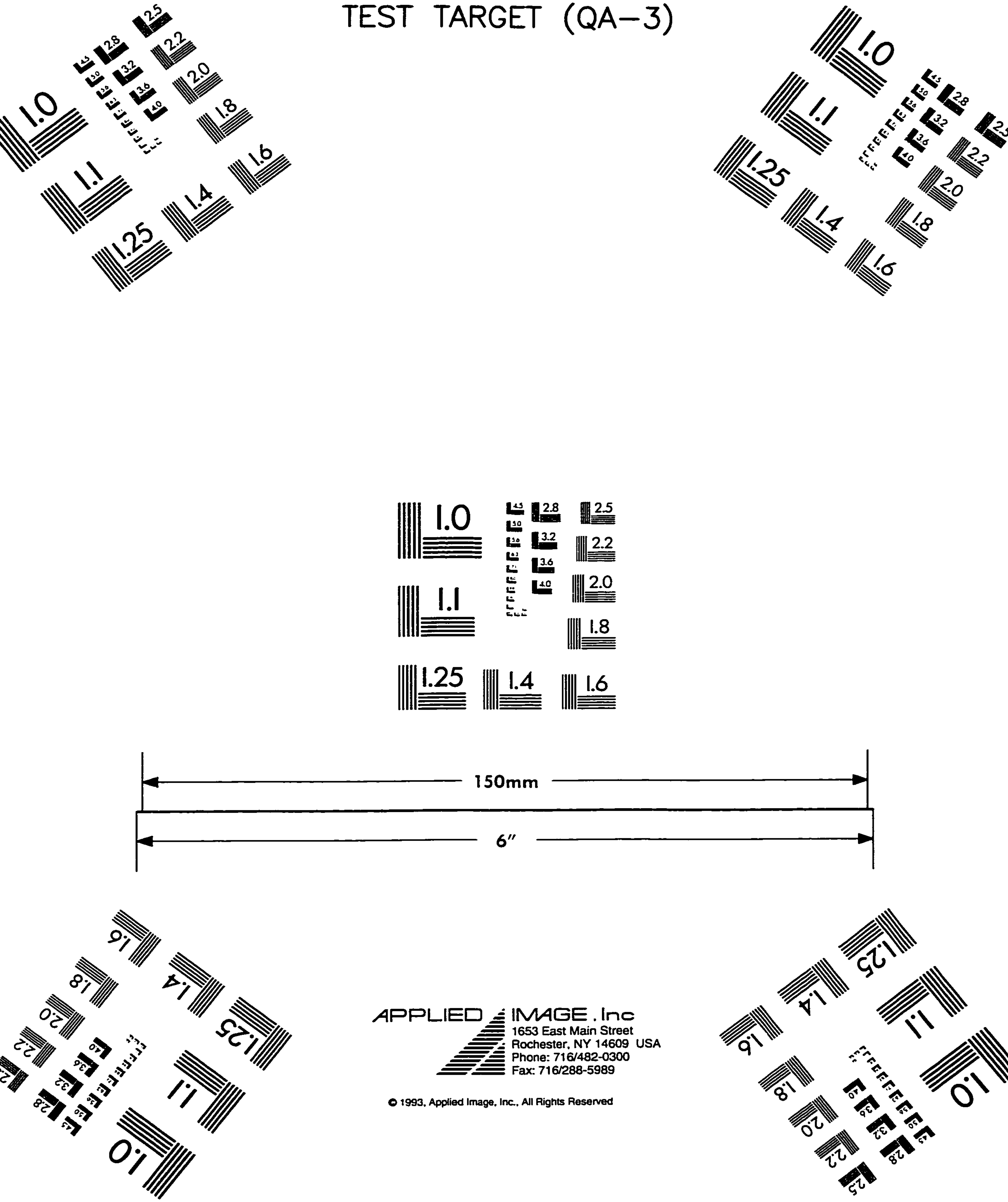
Critical Speed Estimates

Source	*Partial SS*	*df*	*MS*	*F*	*P*
Model	1797.99	27	66.59	109.53	0.0000
Subject	916.72	20	45.84	75.39	0.0000
CS model	881.27	7	125.90	207.06	0.0000
Residual	85.12	140	0.61		
Total	1883.11	167	11.28		

Time Trial Performance

Source	*Partial SS*	*df*	*MS*	*F*	*P*
Model	9628.15	30	321.27	109.29	0.0000
Subject	1485.06	20	74.25	25.26	0.0000
Trial	8153.09	10	815.31	277.34	0.0000
Residual	587.94	200	2.94		
Total	10226.10	230	44.46		

IMAGE EVALUATION TEST TARGET (QA-3)



APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
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