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RESEARCH ARTICLE **Open Access**

The effect of environmental conditions on performance in timed cycling events

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Abstract

Air temperature, pressure and humidity are environmental factors that affect air density and therefore the relationship between a cyclist's power output and their velocity. These environmental factors are changeable and are routinely quite different at elite cycling competitions conducted around the world, which means that they have a variable effect on performance in timed events. The present work describes a method of calculating the effect of these environmental factors on timed cycling events and illustrates the magnitude and significance of these effects in a case study. Formulas are provided to allow the calculation of the effect of environmental conditions on performance in a time trial cycling event. The effect of environmental factors on time trial performance can be in the order of 1.5%, which is significant given that the margins between ranked performances is often less than this. Environmental factors may enhance or hinder performance depending upon the conditions and the comparison conditions. To permit the fair comparison of performances conducted in different environmental conditions, it is recommended that performance times are corrected to the time that would be achieved in standard environmental conditions, such as 20^{o} C, 760 mmHg (1013.25 hPa) and 50% relative humidity.

Keywords: power, air density, temperature, barometric pressure, humidity

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Introduction

Performance in timed cycling events such as the track pursuit, depend upon the balance between the forces that propel and oppose a cyclist's motion. The net propulsive force is determined by the physiological, biomechanical and psychological factors that affect the power that the cyclist can sustain for the duration of the event. The net resistive force is a combination of aerodynamic drag, rolling resistance and internal (mechanical) friction (Martin et al. 1998). Aerodynamic drag accounts for more than 95% of the resistive force experienced by the cyclist at typical race velocities (Martin et al. 1998) and, other than the propulsive force, it is the most important determining factor of pursuit and time trial performance.

The magnitude of aerodynamic drag experienced by the cyclist is proportional to the cyclist's velocity their shape, surface texture and frontal surface area. Other than these factors, aerodynamic drag is also determined by the density of air, in which the cyclist is moving through, which is determined by air temperature, barometric pressure and humidity. There are previous reports that have described the characteristics of aerodynamic drag in cyclists (Martin et al. 2006a, 2006b) and there is a validated mathematical model for calculating both the cyclist's power output for a given velocity (Martin et al. 1998) and their drag coefficient (Heil 2001). There have also been investigations of the optimal position of the cyclist on the bike to minimise their drag coefficient (Jeukendrup and Martin 2001, Lukes et al 2005, Barry et al 2014). However, there have been almost no reports of the effect of changes in air density on aerodynamic drag and subsequent cycling performance. The exception is Bassett et al. (1999) who compared different attempts at the one hour cycling time trial record and corrected for the effect of altitude.

Performance in the track cycling pursuit (3000 and 4000 m), road time trials and the one hour record are sometimes compared for the purposes of team selection, ranking and maintenance of world records. However, the comparison of performances that occur at different times and or places is problematic, because each performance will be affected by different environmental conditions in different ways. Inevitably, the official list of the world's best pursuit and time trial results includes performances that were achieved in differing environmental conditions. In Australia, the relevant national sporting organisation (Cycling Australia) has recently applied a policy (2015, Selection Policy, Part B, Track World Championships) in these situations that requires performance times to be adjusted to standard conditions (24^{o}C, 1013 hPa, 50%RH), but it does not explain the correction method. It is not apparent if relevant organisations from other countries have similar policies. If performances in timed cycling events are to be compared fairly, the effect of all three environmental factors should be accounted for.

Table 1. A summary of the values of the parameters used in equations 1 and 2.

Parameter	Value/s	Rationale
V	45, 50 & 55 km/h	The average velocity of the world records for the men's and women's track pursuit are 53 and 57 km/h. In road time trials, the range is 47 to 52 km/h
Power$_{total}$	302, 406, 532.2 W	The power associated with the velocities used in modelling (above) and other factors (following rows) in standard conditions (20^{o}C, 1013.25 hPa & 50% RH)
Cd	0.3266	Calculated using a formula from Bassett et al. (1999)
A	0.6754 m^2	Calculated using a formula from Heil (2001)
Fw	0.0027	Value reported by Martin et al. (1998)
Crr	0.0033	Value reported by Martin et al. (1998)
m$_{tot}$	71.8 Kg	Based on a 65 kg cyclist and a 6.8 kg bike
G	9.81 m/s^2	Standard constant
Gr	0.0	Horizontal course
Pd	variable	Calculated and dependent upon barometric pressure
Rd	287.058 J/(kg·K)	Specific gas constant for dry air
Pv	variable	Calculated and dependent upon RH and temperature
Rv	461.495 J/(kg·K)	Specific gas constant for water vapour

The purpose of this report is to describe the effect of changes in air temperature, barometric pressure and relative humidity on performance in timed cycling events and to provide a method that can be used to compare and normalise performances, that is both reasonably accurate and simple enough for coaches, officials and sport scientists to implement.

Materials and methods

A published mathematical model of the relationship between power and cycling velocity was used (Equation 1.) to determine the effect of environmental factors on cycling performance. The equation proposed and validated by Martin et al. (1998) was used to explore the effect of changes in air temperature, pressure and humidity on subsequent cycling velocity.

$$Power_{total} = \left(V^3.\frac{1}{2}.\rho.[CdA.F_w]\right) + (V.C_{RR}.m_{tot}.g) + (V.[91 + 8.7.V].10^{-3}) + (V.m_{tot}.g.G_R)$$

Equation 1

A mathematical model of power, velocity and air density

Where; V- velocity of bike and cyclist (m/s), ρ- air density (Kg/m^3), Cd- drag coefficient of cyclist and bike, A- frontal surface area of the cyclist and bike (m^2), Fw- drag area of the spokes, Crr- coefficient of rolling resistance, m_{tot}- total mass (Kg), g- gravitational constant and Gr- grade (slope) of the track/road.

The air density (ρ, Kg/m^3) component of this equation is itself determined by another equation (Equation 2. Brutsaert 1982) that is dependent upon the environmental factors of air temperature, pressure and humidity.

$$\rho_{\text{humid air}} = \frac{p_d}{R_d T} + \frac{p_v}{R_v T}$$

Equation 2

The mathematical relationship between air temperature, pressure, humidity and air density

Where; Pd- partical pressure of dry air (mmHg), Rd- specific gas constant for dry air, T- temperature (K) and Rv- specific gas constant for water vapour. Pv- Pressure of water vapour (mmHg), which is determined by relative humidity (RH) With: $Pv = RH\,.\,Psat$ and, $Psat = 6.1078 \times 10^{\frac{7.5\,T}{T+237.3}}$, where T is temperature in degrees Centigrade, 6.1078 is the water saturation pressure at 0^o C and 237.3 is a vapour pressure constant for water.

Both equations were implemented into a spreadsheet (Microsoft Excel) to automate the calculation of cycling velocity, for given environmental conditions. Since there were only three input variables (temperature, pressure and humidity) that required manipulation and only one output variable (velocity), all other variables in both equations were kept constant. Table 1 lists these variables and the rationale for their value.

A range of values for each of the environmental factors had to be chosen. For temperature, a range of 20 to 30 ^{o}C was chosen to approximate the range of temperatures encountered by pursuit and time trial cyclists. For barometric pressure, a range of 580 to 780 mmHg (780-1040 hPa) was used as it encompasses the low pressures encountered at altitude (~2000m) and the higher pressures encountered at sea level when a high pressure weather system is present. The range of values for relative humidity was chosen to be 30 to 80 % based on typical values found in a variety of indoor (enclosed velodrome) and outdoor (outdoor track or road time trail course) venues where cycling events are held.

The effect of changes in the three environmental factors on cycling velocity was determined using an iterative process. Firstly, a baseline condition was established using 20 ^{o}C, 760 mmHg (1013.25 hPa) and 50% relative humidity. This choice was based on a gas standard published by the International Standards Organisation (ISO 5011:2014) that also falls within the typical range of conditions encountered by cyclists. For the values listed in table 1, the subsequent power was calculated, 302, 406, 532.2 W for the velocities of 45, 50 and 55 km/h respectively. The effect of changes in temperature on cycling velocity was determined by keeping pressure and humidity constant, and by changing the value for temperature incrementally by 1 degree. A large table of results was then generated that recalculated power for a range of velocities. In this table, the velocity that was associated with the power output equal to the baseline condition represented the actual velocity that would have been produced as a result of the change in temperature. In this process, power was matched to the precision of one decimal place (0.1 W). Velocity was recorded in km/h to three decimal places. This stepwise approach was used across the stated range of values for each of the three environmental factors and for each of the three modelled velocities (45, 50 and 55 km/h).

The iterative calculation process generated tables of results that revealed the association between the three environmental variables and the subsequent changes in cycling velocity. The results were analysed to determine correction factors that could be used to conveniently determine the net effect of changes in environmental conditions on velocity, for a fixed average power output in a cycling event. The magnitude of these correction factors are themselves dependent upon velocity, which is why the entire analysis was completed for three velocities (45, 50 and 55 km/h). Equations were then derived to accurately calculate these correction factors, based on velocity.

Across the range of values for each of the environmental factors and for all three velocities modelled, the relationships between each of the environmental factors and velocity were effectively linear, achieving Pearson correlation coefficients of r=0.9938 to 0.9999. Figures 1A, B & C. present the relationships between the environmental factors and cycling velocity, modelled for three different velocities. The slope of each of the three lines in each figure represents the rate at which velocity changes, in response to changes in each of the environmental factors. In other words, the slopes of the lines represent the magnitude of the factors that can be used to determine the effects of environmental conditions on cycling velocity.

The slopes of each of the three lines in each of figures 1A, B & C are subtly different, because they vary in proportion to velocity themselves.

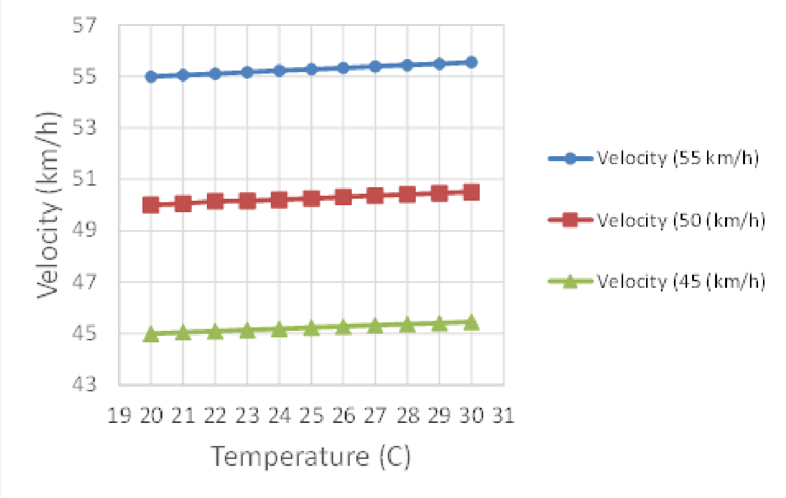

Figure 1A

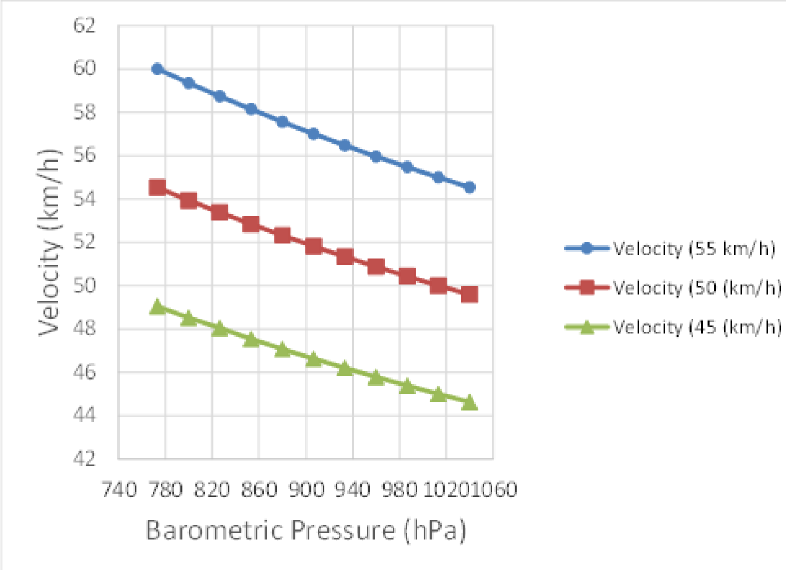

Figure 1B

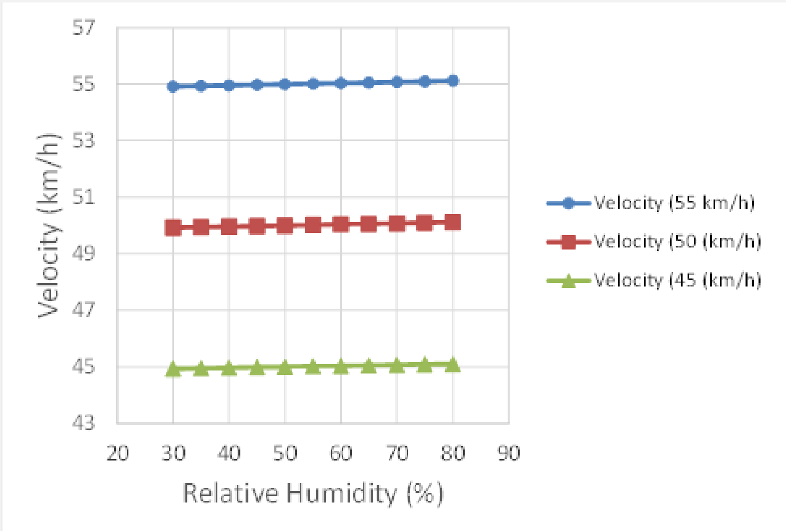

Figure 1C

Figures 1 A, B & C. The relationships between environmental factors and cycling velocity. Changes in velocity represent predictions, based upon an assumption of constant power output and the effect of the change in each factor on air density. The relationships between environmental factors and velocity were modelled for three different velocities that approximate the typical range of velocities achieved in pursuits and road time trials.

Figures 2A, B & C present the effect of velocity on the magnitude of the slope values that appear in Figures 1A, B & C. A curve (second order polynomial for temperature) and lines were fitted to the data points to generate formulas to accurately calculate the correction factors, for given velocity. These formulas are as follows;

A. Temperature correction factor (km/h per $1^{o}C$) = $0.00003800 \cdot v^2 - 0.00273000 \cdot v + 0.091100$
B. Pressure correction factor (km/h per 1 hPa) = $-0.000400 \cdot v - 0.001500$
C. Humidity correction factor (km/h per 1% RH) = $0.000080 \cdot v - 0.000300$

Equations 3 A, B & C

The equations determine the correction factor for each environmental factor, based upon the average velocity achieved in the event that is being analysed. V is velocity (km/h).

The temperature correction factor, represents the increase in velocity (km/h) that occurs with $1^{o}C$ of increase in temperature above 20^{o} C. The pressure correction factor, represents the increase in velocity (km/h) that occurs with 1 hPa decrease in barometric pressure, below 1013.25 (760 mmHg). The humidity correction factor, represents the increase in velocity (km/h) that occurs with 1% of increase in relative humidity above 50%. As the correction factors have a nearly perfect linear relationship with velocity across the range of velocities modelled here, they can be used as simple multipliers. The correction factors can be applied to calculate the effect of increases and decreases in any of the environmental factors.

Case Study

- The current men's 4000m pursuit world record is 4:10.534 (mm:ss.sss) and was set on 02/02/2011 in the Olympic Velodrome in Sydney, Australia. The conditions in the velodrome were $33^{o}C$, 1012.4 hPa and 63% RH (The author was present at this event to make and record these measurements).
- Using the event time and distance to determine the average velocity of the event (57.477 km/h), equations 3 A, B & C can be used to calculate the correction factors for each environmental factor. They are;
    - Temperature, 0.05972 km/h faster, per increase in 1 degree C above 20
    - Pressure, 0.02149 km/h faster, per decrease in 1 hPa below 1013.25
    - Humidity, 0.00429 km/h faster, per increase in 1 %RH above 50 %RH
- Applying these correction factors to determine how performance would have changed if it were conducted in standard conditions of 20 ^{o}C, 760 mmHg (1013.25 hPa) and 50% RH (ISO 5011:2014), yields the following changes in velocity;
    - Temperature, 0.77642 km/h faster
    - Pressure, 0.01826 km/h faster
    - Humidity, 0.05587 km/h faster
    - Total net change in velocity due to environmental conditions is 0.85057 km/h faster
- Adjusting the actual average velocity achieved in this event, by the net change in velocity (subtraction in this case) allows the prediction of the 4000 m pursuit time, notwithstanding the limitations of this method, that would have been achieved by this cyclist in standard conditions; 4:14.297 (mm:ss.sss).

This case study indicates that the ideal conditions in which this event was conducted, allowed the cyclist to record a time that was approximately 3.763 s faster (1.5%), than if it had have been conducted in standard conditions. Indeed if it were performed in standard conditions, and the cyclist had produced the same average power, they would probably not have broken world record which was 4:11.114 (mm:ss.sss) at that time.

Discussion

The present analysis reveals the effects of air temperature, pressure and humidity on velocity and therefore performance in a timed cycling event. The findings highlight the need for and provide a method to fairly compare performances in timed cycling events.

The relationships between environmental factors and cycling velocity are relatively complex. The present results illustrate that the relationships themselves are dependent upon velocity. For all three environmental factors, the magnitude of the correction factors increase as the average velocity of the performance increases. The differences are small but important and so velocity based equations to calculate the correction factors are reported, rather than constant values to be used for all velocities.

The magnitude of the effect of changes in each environmental factor on velocity is different. In general, changes in temperature have the largest effect on velocity, followed by pressure and then humidity. In addition, the direction of these effects is not all the same. Velocity increases with increases in temperature and humidity, conversely velocity decreases with increases in pressure.

The magnitude and direction (faster or slower) of the effect of each environmental factor on cycling velocity, depends entirely on the conditions being compared. Cycling events are conducted at venues around the world in environmental conditions that vary according to latitude, altitude, season, weather pattern and the effects of a climate control system in an enclosed velodrome on temperature and humidity. In some situations altitude may be the most important factor and in others temperature may be more important. It is also possible that two factors may have opposing effects on cycling velocity (e.g. when there is a small increase in temperature and a large increase in barometric pressure).

Having an understanding of the effects of environmental factors on cycling performance provides the opportunity to manipulate the environmental conditions to improve performance. In general, ideal conditions can be described as relatively high temperature, low pressure and high humidity. Of course these "ideal" conditions may have deleterious effects on performance due to their effect on physiological capacity, but this depends upon the event and the physiology of the athlete. The identification of the combination of environmental conditions that optimises the complex interaction of air density and physiology would be very difficult, but certainly advantageous.

The results presented here are not based on empirical data, but on a mathematical model of the relationship between air density and cycling velocity. The exact relationship is very complex and would incorporate more than the ~16 parameters in the equations presented here. In addition, some of the parameters required to make a nearly perfect model, are either not typically measured in cycling events (e.g. the rate and duration of acceleration from a standing start) or they are not feasible to measure (e.g. the increase in the vertical force on tyres when cornering and the subsequent effect on Crr). If a nearly perfect model were developed, it would require a significant increase in the measurement of the performance of cyclists, such as a continuous measure of velocity, which would necessitate the use of measurement technology on all bikes. The calculation process would almost certainly have to be implemented into software, as it would probably involve the calculation of the correction factors for each second of the event. These initiatives would require the endorsement of the International Cycling Union (UCI), as they would involve rule modifications and additions to ensure accuracy of measurement and there would be a cost of compliance for cyclists.

Given these complications, the aim of this study was to identify a model that is a compromise between accuracy and practical feasibility. The relationship between environmental conditions and velocity was intentionally simplified to make it feasible which undoubtedly limits its accuracy. Several parameters that are specific to each individual cyclist and bike (e.g. CdA and mass), were fixed at values deemed to be

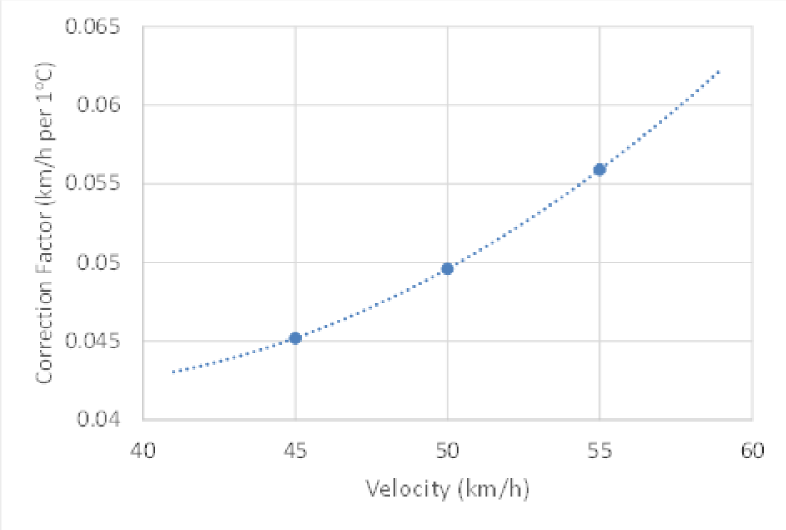

Figure 2A

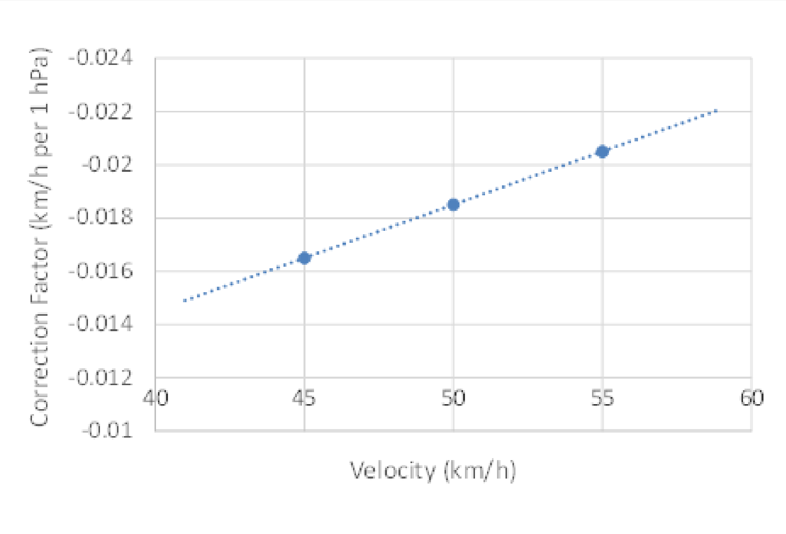

Figure 2B

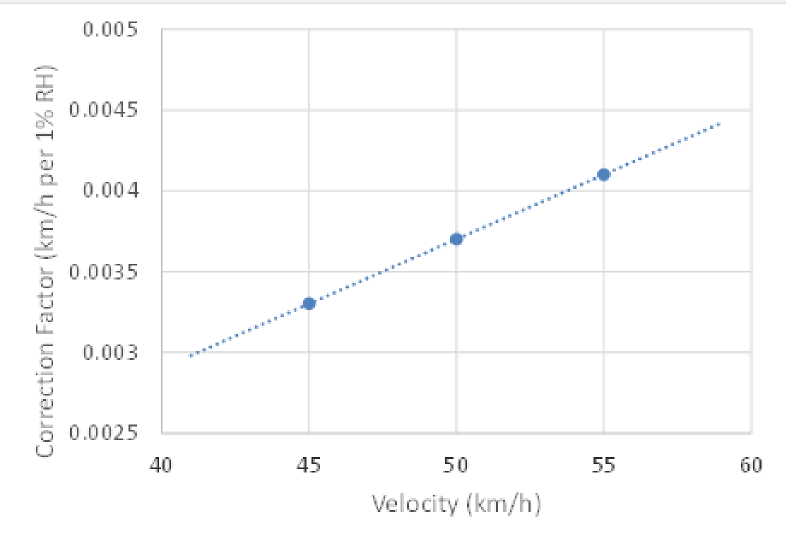

Figure 2C

Figures 2 A, B & C. The relationship between velocity and the correction factors used to determine the effect of environmental factors on cycling velocity.

typical of elite athletes who compete in timed cycling events. The coefficient of rolling resistance was fixed at a relatively optimal value rather than attempting to model it's fluctuations with temperature and tyre pressure. The model assumes a constant velocity for the event and ignores the period of acceleration at the start of most timed cycling events and the small variation in velocity that occurs around the bends of a velodrome. Nevertheless, the model provides a method of approximating the effect of environmental conditions on cycling performance, where no alternatives currently exist. In addition, it is arguably better to implement an approximation of environmental effects in a consistent way, than to do nothing at all. The correction factors are useful for events conducted in controlled conditions (i.e. velodrome), where velocity is relatively constant. The factors would be less valid if applied to events conducted in uncontrolled conditions (e.g. road time trial in wind affected conditions) and in events where velocity is not constant (e.g. the 500 and 1000 m TT). The correction factors apply to velocity, rather than time over a fixed event distance, which allows them to be applied to events of different distances.

Practical applications

Environmental conditions can have a significant effect on performance in timed cycling events. Comparison of performances for the purposes of team selection and record keeping should allow for these environmental effects. Correction of performance times to standard conditions is a suitable way to compare performances achieved in different environmental conditions. It is recommended that these standard conditions be; 20^{o} C, 760 mmHg (1013.25 hPa) and 50% relative humidity (ISO 5011:2014). The present report provides a method of calculating the effect of temperature, pressure and humidity on performance in a timed cycling event.

Conflict of interest
The author has no conflicts of interest that are relevant to this work.

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