# Model-Based Real-Time Monitoring of Cyclist Thermal Comfort for Smart Helmet Applications

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## 1 INTRODUCTION

Bicycling, for recreational, transport or sport purposes, is contributing to health benefits for the individual as well as for the society [1]. However, due to different reasons bicyclists can be subjected to crashes, which can cause injuries over the whole body. Of these accidents, head injuries can lead to serious brain damage and in extreme cases to dead [2]. Head injuries can be prevented by wearing bicycle helmets [3], which can be lifesaving in particular cases. However, bicycle helmets are not worn frequently due to a variety of reported [4] barriers of social, psychological, cultural and/or biological origin. One of the most returning complaints for bicycle helmet-wearing appears to be thermal discomfort (Finnoff et al., 2001). Therefore, it is of utmost importance that bicycle helmets are designed in a way they favour thermal comfort whilst meeting the protection requirements. This dual goal of protection and comfort poses a great challenge because of the potential contradictory requirements in achieving thermal conditions and protective capacity [7]. Bicycle helmets are mainly made of insulating foams, whereby the natural heat losses from the head are obstructed leading to an increase of the temperature in the space between bicycle helmet and scalp, consequently, to excessive sweating and the accompanied perception of thermal discomfort. This research work aims at developing a real-time model-based algorithm for monitoring the cyclist's thermal comfort under the bicycle helmet, including investigating the contribution of the bicycle helmet in the personal perceived thermal comfort.

## 2 EXPERIMENTS

In total, 15 male test subjects with an average age of 22 years (± 1 year) and average weight of 74.3 kg (± 9.2 kg) are used to perform the designed thermal comfort experiments during the course of this research work. The experimental protocol are included two stages on-bicycle experimental trials, pre-test trials followed by thermal comfort trials.

### 2.1 Pre-test trials

The aim of the pre-test trials is to measure the maximum delivered cycling power that can be maintained by each test subject for at least 20 minutes [8] in order to ensure that each test subject is able to persevere the course of the thermal comfort trials. Starting from 100 Watts, bicycle step-increases in the cycling power with incremental rate of 30 Watts every 5 minutes are performed. During the pre-test, the *Respiratory Exchange Ratio* (RER) of each test subject is measured using a *Spirometer* (Metamax® 3B). The test is terminated when the RER, for any of the test subjects, exceeds the value of one for more than 20 seconds. The pre-test trials are conducted at ambient air temperature and relative humidity of 20 ºC and 47%, relatively. A bicycle trainer (Tacx IRONMAN® Smart) with a fastened racing bicycle (BH L52C8 Speedrom®) controls the power delivery by the subject.

## 2.2 Thermal comfort trials

The thermal comfort experiments are designed in such way to investigate the effect of environmental variables (ambient air temperature, relative air velocity, power delivered and thermal resistance of the scalp, which is induced by bicycle helmet wearing) on the cyclist's thermal comfort. The trials are conducted within a climate-controlled chamber, with the dimension 4m×12m×5m ($w$×$l$×$h$). The air temperature within the climate chamber is controlled within the range of 15-35 ºC. Additionally, the ventilation rate within the climate chamber is controlled within the range of 0-2700 $m^3$/h (i.e., 0-11.25 volume refreshment per hour). The bicycle trainer together with the bicycle are placed inside a customized wind tunnel (2.3m×1.5m×2.1m). The wind tunnel is equipped with 12 fans, arranged in a 3×4 array, to deliver a maximum air velocity ($v$) of 4 m/s (see Figure 1). Each trial is taken 80 minutes and divided into 4 consecutive timeslots of 20 minutes each. At each timeslot, a combination of changes in the environmental variables, namely, relative air velocity ($v$), ambient air temperature ($T_a$), thermal resistance of the scalp ($R_h$) and the delivered cycling power ($P$), is applied. The applied combinations are included different levels (i.e., low, mid and high) of changes in each variable as shown in Table 1. An example of the applied combination of changes in the environmental variables, for subject #1, is shown in Table 2. During the experiment, the test subjects are verbally asked, every 5 minutes, about their thermal comfort sensation from the start until the finish (minute 80) of the trial. The answered values of these sensation are ordinal categories of the scale according to Gagge's [9] thermal comfort ($TC$) scale (i.e., $TC \in$ [1(=$comfortable$) and 4 (=$very\ uncomfortable$)]). A static linear regression model is made to express the $TC$ in terms of the environmental variables so that more insight is acquired in the specific contribution of bicycle helmets to the cyclist's thermal comfort.

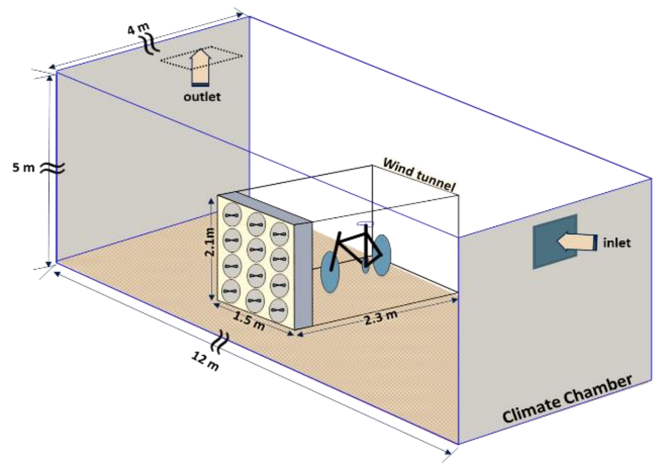


*Figure 1. Schematic representation showing the used training bicycle fixed inside a customized wind tunnel and placed within the climate chamber.*

*Table 1. The applied different levels of changes for each variable.*

| | $T_a$ [°C] | $v$ [m/s] | $P$ [$W$] | $R_h$ [$m^2$°C/$W$] |
|---|---|---|---|---|
| Low-level | 20 | 0 | 50%$P_{RER=1}$ | 0 |
| Mid-level | / | / | / | 0.045 |
| High-level | 30 | 4 m/s | 90%$P_{RER=1}$ | 0.060 |

*Table 2. Experimental design for test subject #1, showing the combination of changing environmental variables.*

| Subjects (no. *i*) | Variables | Timeslot 1 | Timeslot 2 | Timeslot 3 | Timeslot 4 |
|---|---|---|---|---|---|
| $\boldsymbol{i = 1}$ | $T_a$ (°C) | 20 | 20 | 20 | 20 |
| | $v$ (m/s) | 4 | 0 | 4 | 0 |
| | $P$ (% $P_{RER=1}$) | 50 | 50 | 90 | 90 |
| | $R_h$ ($m^2$ °C/W) | 0.045 | 0.060 | 0.045 | 0 |

## 3 RESULTS AND CONCLUSIONS

The results show that wearing a bicycle helmet has a significant (p-value < 0.05) effect on the thermal comfort sensation of the tested subjects. To investigate the steady-state effect of bicycle helmet on the thermal comfort sensation, a linear regression model (equation 1) is identified, in which the resulted thermal comfort ($TC$) is used as an output while the four environmental variables are the inputs to the model. Table is showing the model estimates of the model parameters.

$$TC = \alpha + \beta_1 T_a + \beta_2 v + \beta_3 P + \beta_4 R_h \quad (1)$$

*Table 3. Average model parameter estimates for the 15 test subjects.*

| Term | Estimate | Standard Error |
|---|---|---|
| Intercept $\alpha$ | 2.363 | 0.141 |
| $\beta_1$ | -0.396 | 0.112 |
| $\beta_2$ | -0.359 | 0.074 |
| $\beta_3$ | 0.412 | 0.075 |
| $\beta_4$ | 0.250 | 0.099 |

The results show that the identified dynamic models have the potential to be implemented in real-time to monitor the thermal comfort status of the cyclists. Hence, the bicycle helmet can be used as monitoring device by integrating environmental sensors (e.g., air and head temperatures and heart rate) in the helmet.

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